Thesis for the Degree of Doctor of Philosophy

Stock-recruitment relationships incorporating environmental factors and optimal harvest rates of jack mackerel (*Trachurus japonicus*) around Korean waters

by

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University-Research Institute Interdisciplinary Program of

Fisheries and Oceanography

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(한국 주변해역 전갱이의 환경변동을 고려한 산란량-가입량 관계 및 적정어획생산율)

Advisor: Chang Ik Zhang

by

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A dissertation

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한국 주변해역 전갱이의 환경변동을 고려한 산란량-가입량 관계 및 적정어획생산율

이 재 봉

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요 약

한국 주변해역의 물리적 해양환경 변동은 38년간 157개 해양관측 정점의 표층 및 50m층 수심에서 해수밀도를 사용하여 분석되었다. 한국 동해, 남해, 서해에 해당하는 3개의 해수특성이 자가구성법(SOM)에 의해 나뉘어졌다. 이러한 3개의 해수특성을 파엽분석한 결과, 1970년대 후반부터 1980년대 후반까지 8-16년의 십년주기 주파수가 강하게 나타났다. 또한, 쿠로시오 해류의 표층 흐름은 1980년대에는 주로 서쪽으로 흐른 반면, 1990년에는 동쪽으로 흘러 일본 큐슈 서편으로 이동하였다. 주요 생물 해양환경인자 중의 하나인 동물성플랑크톤의 생체량은 지역적 규모의 물리환경환경인 전갱이 주서식장의 해수온도 및 전지구적 규모의 물리환경인자인 POD 및 SOI 지수와 유의한 상관성을 나타냈다.

해류수송유래 가입 가설에 의거 한 가입성공은 전년도 산란자원량의 풍도 및 분포, 전갱이 주서식장에서의 먹이 이용도 및 수온에 의해 결정되었다. 연속자료처리기법을 사용하여 1968-2004년의 전갱이 어획량, 자원량 및 산란자원량과 관련하여 해양환경 시계열 자료의 체제전환 즉 비연속성이 분석되었다. 전갱이의 산란량-가입량 관계는 1976년과 1987년에 유의하게 변동되었으며, 3개의 체제를 고려한 가입량 추정치는 전갱이의 실제 가입량 변동과 매우 유의한 상관을 나타냈다($P<0.001$). 한국 주변해역의 전갱이 가입량, 산란자원량 및 주서식장 환경인자간의 관계를 구명하기 위해 일반선형모델(GAM)이 분석되었다. 전갱이의 가입량 시계열은 *loess* (weighted local regression smoother) 함수에 의해 1989-2003년의 산란자원량, 동물성플랑크톤 생체량 및 PDO에 의해 가장 잘 설명되었다.

전갱이 자원의 적정어획생산율은 처녀 가입당산란량의 30-35% 내에서 추정되었으며, 어떠한 산란량-가입량 관계(SPR)에 대해서도 최대 지속적생산량에 가까운 어획생산을 달성할 수 있는 수준이다. 또한 전갱이의 F_{MSY} 대리추정치를 설정하기 위한 SPR 어획생산율이 계산되었다. 적정어획생산율을 기초로 하여 최대어획사망임계수준(MFMT)이 정의되었으며, 이는 주요 전갱이 대상어업의 적정어획생산을 달성하는 동안에는 남획을 방지할 수 있는 수준이다. 현행 어업관리 제도에 사용되는 5단계 시스템은 한국 주변해역의 전갱이 자원의 ABC 뿐만 아니라 OFL을 포함하는 새로운 단계 시스템으로 정비될 수 있을

것이다. 한국 주변해역의 전갱이 자원에 대해 호조건의 해양환경 상태에서 2단계 수준에서 OFL 및 ABC는 환경인자를 결합하였을 경우와 환경인자를 고려하지 않은 기존의 경우와 비교할 때 각각 약 13,000톤 및 10,000톤 가량 높은 것으로 산정되었다.

Stock-recruitment relationships incorporating environmental factors and optimal harvest rates of jack mackerel (*Trachurus japonicus*) around Korean waters

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Abstract

Physical ocean environments around Korean waters were examined using seawater density at surface and 50m layer depth from 157 stations over 38 years. Three water properties, corresponding to the East Sea, East China Sea, and Yellow Sea of Korea, were categorized by self-organizing mapping (SOM). Wavelet spectra of these three water-properties exhibited strong decadal frequencies of 8-16 years from the late 1970's to the late 1980's. The ocean surface current of the Kuroshio Current drifted westwards during the 1980's and moved eastwards to the western area of Kyushu of Japan during the 1990's. Zooplankton biomass, one of major biological ocean environmental factors, showed a positive significant correlation with local scale physical environment,

such as sea water temperature in major habitat of jack mackerel and with global scale physical environment, such as PDO and SOI indices.

Based on the hypothesis of advection-based recruitment, successful recruitment was dependent on the abundance and distribution of spawning biomass in the previous year, food availability and temperature in the major habitat of jack mackerel. Using a sequential data processing technique, a regime shift, or discontinuity, was tested in ocean environmental time series relative to the catch, recruitment and spawning biomass of jack mackerel for 1968-2004. The spawning biomass and recruitment relationship of jack mackerel shifted in 1976 and 1987, and the recruitment estimate considering three regimes was highly significantly correlated with recruitment of jack mackerel ($P<0.001$). Generalized additive models (GAM) were developed to explore relationships between jack mackerel recruitment, spawning biomass and environmental variables in the major habitat area of jack mackerel around Korean waters. The time-series of estimated recruitment by the function of *loess* (weighted local regression smoother) with spawning biomass, zooplankton biomass and PDO provided the best explanation for the period of 1989-2003.

The optimal harvest rate of jack mackerel was estimated to be within the range of 30-35% of the unfished level of spawning biomass per recruit (SPR) that provides a yield near MSY for any probable spawner-recruit relationship (SRR). The SPR harvest rate required for establishing an F_{MSY} proxy for jack mackerel

was also examined. Based on the optimal harvest rate, a maximum fishing mortality threshold (MFMT) was defined, which prevents overfishing while still achieving an optimal yield form the major jack mackerel fishery. For potential refinement of the present management system, a revised five tier system was developed that included an overfishing level (OFL) as well as acceptable biological catch (ABC) of jack mackerel around Korea waters. In tier 2 under favorable marine environmental conditions for jack mackerel around Korean waters, OFL and ABC estimated with incorporating environmental factors were about 13,000 and 10,000 mt higher, respectively, than those estimated with customary formation of the SRR.

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CHAPTER 1

INTRODUCTION

The regeneration processes of fish populations are critical to the maintenance of sustainable abundance levels (Quinn & Deriso, 1999). It is clear that there must be some bounds on recruitment during early life history stages, due to ecological limits such as food, spawning area, rearing area, or cannibalism. Marine fish species with pelagic eggs or larvae often show substantial fluctuations in recruitment, which may be attributed to environmental factors affecting early life stage's abundance, growth and survival (Hjort, 1914; Cushing, 1975; Lasker, 1978; Peterman et al., 1988). Physical environmental factors, such as temperature and wind, have been recognized as essential factors for population regulation in marine ecosystems (Cushing, 1982, 1995; Sinclair, 1988; Rothschild, 1995; Steele, 1995; Bakun, 1996). The ocean physics have been assumed to influence fish recruitment directly or by regulation of the availability of larval food, that is, the plankton production (Daskalov, 1999; Zhang & Lee, 2001). Environment-recruitment relationships have been studied in highly productive areas such as shelf areas of the Northwestern Pacific and the North Sea where environmental factors showed relatively clear patterns and there was general understanding of casual links between ocean physics, plankton productivity and recruitment success (Zhang et al., 2000; Reid et al., 2001). In the Black Sea, sea surface temperature (SST), atmospheric pressure and juvenile fish abundance surveys data were used to forecast year-class strength and migration of pelagic fish, such as anchovy and horse mackerel (Simonov et al., 1992).

Jack mackerel mainly spawned along the shelf-break regions of the East Chia Sea, though small-scale regional spawning was also reported in the coastal regions of Kyushu, Shikoku and Honshu Islands of Japan in the 1960's (Asami, 1974). A recent ichthyoplankton survey showed that main spawning ground of jack mackerel was formed in the southern East China Sea south of 28°N from late winter to spring, and juveniles of jack mackerel were found in the northern East China Sea off the west coast of Kyushu Island of Japan in April (Sassa et al., in press). The appearances of larvae and juveniles of jack mackerel from different area and time in the East China Sea were explained with the transportation to the adjacent of Korean waters by the Tsushima Warm Current, which is a branch of the Kuroshio Current. Fluctuations in the geographic position of the Kuroshio current were considered to affect the formation of the spawning grounds and transportation of fish eggs and larvae in the ECS and around Korean waters (Kim, 2002, Sassa et al., in press).

Based on a larval fish transport in the East China Sea, it was examined whether annual fluctuation of the Kuroshio Current may directly influence variations in recruitment and biomass of jack mackerel or regulate the plankton production around Korean waters.

The purpose of this thesis is (1) to examine the role of fluctuations of the Kuroshio Current as a factor affecting the transport of jack mackerel eggs and larvae from the main spawning ground to the nursery grounds, (2) to investigate whether environmental factors could affect the abundance of jack mackerel, (3) to develop a stock-recruitment relationship incorporating environmental factors, and (4) to estimate acceptable biological catch and overfishing level for jack mackerel for developing a sustainable harvest strategy considering environmental factors around Korean waters.

The process for investigating stock-recruitment relationship and optimal harvest rate of jack mackerel around Korean waters was shown in Fig. 1-1. The process of 14) was described in chapter 2, processes of 1) through 12) were in Chapters 3, and those of 13) through 17) were in Chapter 4 of this dissertation.

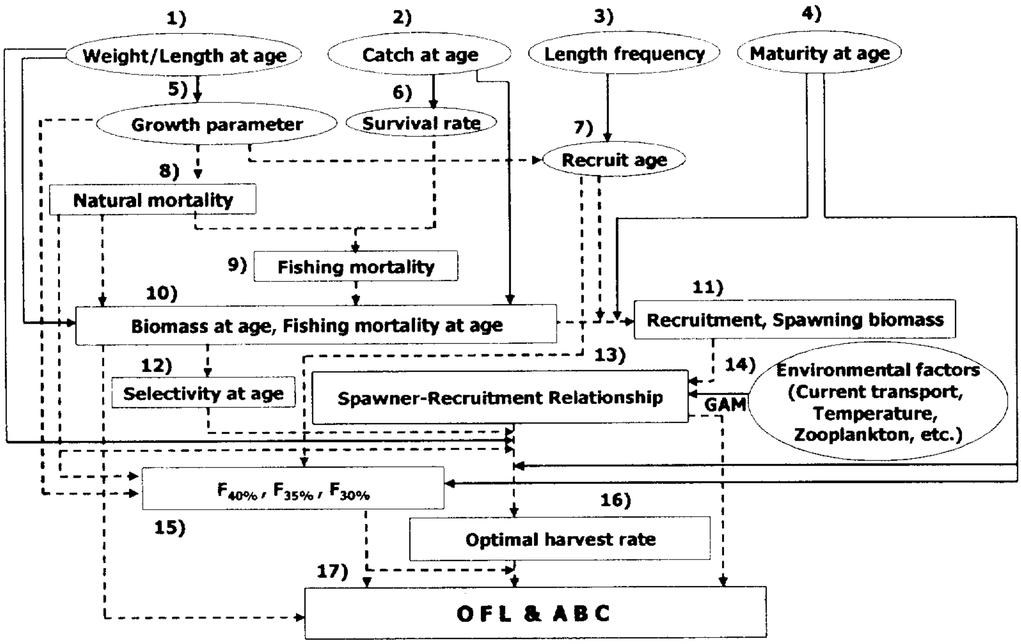

Fig. 1-1. Flowchart describing the process of investigating stock-recruitment relationship and optimal harvest rate of jack mackerel around Korean waters. Circles indicate input data and ecological parameters, rectangles mean stock assessment models and its output. Abbreviation: GAM = Generalized additive model, OFL = Overfishing level, ABC = Acceptable biological catch.

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CHAPTER 2

OCEAN ENVIRONMENT AND DISTRIBUTION OF JACK MACKEREL STOCK AROUND KOREAN WATERS

2.1 INTRODUCTION

The jack mackerel (*Trachurus japonicus*) is widely distributed in the East Asian seas and one of the most important fishery resources in Korea, Japan, and Taiwan (Zhang & Lee, 2001; Sassa et al., in press). Jack mackerel are highly migratory fish that inhabit in warm pelagic environments. They occur throughout Korean waters, especially in the entire continental shelf region of the southern Japan/East Sea (JES), the Yellow Sea (YS) and the East China Sea (ECS). In the ECS, the main distribution area of jack mackerel larvae is in the Kuroshio frontal area along the continental margin during winter and spring (Sassa et al., in press).

Based on biological characteristics and fisheries data, the spawning grounds of jack mackerel could be divided into three areas around Korean waters: northern Kyushu, middle ECS, and southern ECS (Kim, 2002). Kim (2002) noted that the spawning concentration in the middle of ECS was targeted by commercial fisheries and the abundance of spawner was related to the abundance of jack mackerel around Korean waters.

Because jack mackerel are usually short-lived, any fluctuation in recruitment success translates rapidly into fluctuations in population size. Therefore, what may be a conservative level of exploitation during years with good recruitment may result in overfishing during unfavorable years. Recruitment success can be thought of as an integrated function of processes acting across a wide range of life-history stages, from the size and condition of the spawning population at one end to the pre-recruit survival rates at the other (Cole & McGlade, 1998). Dealing with specific sources of egg and larval mortality, 'Advection'-based theories are concerned with the transport of eggs and larvae towards or away from suitable nursery areas (Iles & Sinclair, 1982).

The objective of this chapter is to investigate abrupt shift, that is, discontinuity in ocean environmental time series data of Korea and adjacent waters for 1968-2004. I hypothesized that successful recruitment was dependent on advection processes; specifically, eggs and larvae of jack mackerel was transported from spawning grounds in the ECS to nursery grounds in the western Kyushu of Japan. If so, the recruitment of jack mackerel is dependent on the abundance of spawning biomass, which will be described in Chapter 3, in the previous year and advection during the spring.

2.2 MATERIALS AND METHOD

I categorized physical ocean environments using data on seawater temperature, salinity and density at surface and 50m depth layers. These data were taken from 157 stations and stored at the Korea Ocean Data Center (KODC) over 38 years (1965-2003) and divided water-masses around Korean waters using self-organization mapping (SOM). SOM is one of many potential neural network pattern recognition techniques that seek clusters in data using unsupervised learning methodology (Lek & Guegan, 1999; Chon et al., 1996).

To analyze the potential advection of jack mackerel larvae from spawning areas to nursery grounds in a given year, the ocean surface current simulation (OSCURS) model was employed in conjunction with known temporal and spatial information on jack mackerel distribution. The OSCURS model produces an index of surface flow in the oceanographic environment of the North Pacific (Ingraham *et al.* 1998). The northern flow is a representative of the intensity and direction of large scale atmospheric forcing and the Kuroshio currents northward. OSCURS drift trajectories were estimated from release points located in the major spawning ground of jack mackerel in the East China Sea, based on the ichthyoplankton survey by Sassa et al.(in press). Current flows used in this paper were derived from the selected release points located at 26°N 123°E starting from February, which have been known to be related to the abundance of jack mackerel around Korean waters. Based on habitat distributions of jack mackerel around Korean waters, I defined the 'touch down zone' where larval jack mackerel settle out of the planktonic larval stage within 32°-35°N and 125°-131°E. Within this zone I collected temperatures and salinities at the surface and 50m layer depth, estimated zooplankton biomass in April and counted the number of days that OSCURS trajectory stayed within the zone during April-June of 1968-2004.

Seasonal and monthly distributions of jack mackerel were monitored by calculating confocal ellipses and centroids in the fishing ground of jack mackerel in Korean waters from 2000 to 2002. The catches by fishing block of jack mackerel from the Korean purse seine fisheries in Korean waters were archived on Fisheries Resources Research (FIRR) Database in the National Fisheries Research and Development Institute (NFRDI) of Korea.

Jack mackerel are usually caught by large purse seiners, bottom trawls and drift gill nets in Korean waters. About 80% of the total jack mackerel catches are from the large purse seine fishery, mostly in Korean waters within the ECS. Assuming the locations of purse seine fishing vessels as the representation of jack mackerel habitat, a confocal ellipse was calculated as follows:

$$(\bar{X},\bar{Y}) = \left(\frac{\sum_i Catch_i \cdot X_i}{\sum_i Catch_i}, \frac{\sum_i Catch_i \cdot Y_i}{\sum_i Catch_i} \right)$$

where, X and Y are longitude and latitude of the fishing block i, $\bar{X}$ and $\bar{Y}$ are the confocal of the ellipse, respectively. The ellipse can be described by two principal axes of the fishing grounds, the major axis and the minor axis at right angles to each other, and the major axis is the longest possible axis of the ellipse (Sokal & Rohlf, 1995). The slope (b_1) of the principal axis is computed from:

$$b_1 = \frac{s_{12}}{(\lambda_1 - s_1^2)}$$

where, s_{12} is the covariance of longitude (X) and latitude (Y) of the fishing block weighted by catch in the purse seine fishery, s_1^2 is the variance of Y, and λ_1 is a quantity defined as follows in terms of variances and covariance of X and Y:

$$\lambda_1 = \frac{1}{2}\left[s_1^2 + s_2^2 + \sqrt{(s_1^2 + s_2^2)^2 - 4(s_1^2 s_2^2 - s_{12}^2)}\right]$$

The slope (b_2) of the minor axis, that is at right angles to the slope of the principal axis, is equal to -1 / b_1. To describe the shape of an ellipse, the ratio of the lengths of its major and minor axes was computed as the ratio λ_1 / λ_2, where $\lambda_2 = s_1^2 + s_2^2 - \lambda_1$.

The analyses in this study focused on the relationships between jack mackerel abundance and environmental variables in the Korean waters.

I used a sequential data processing technique to detect a regime shift, or discontinuity, in time series (Rodionov, 2004). In the sequential analysis the number of observations is not fixed. Instead, observations come in sequence. For each new observation a test is performed to determine the validity of the null hypothesis H_0 (existence of an abrupt shift). There are three possible outcomes of the test: accept H_0, reject H_0, or keep testing. I determined the difference (*diff*) between mean values of two subsequent regimes that would be statistically significant according to the Student's t-test:

$$diff = t\sqrt{\frac{2\sigma_l^2}{l}}$$

where t is the value of t-distribution with $2l$-2 degrees of freedom at the given probability level p. l is the cut-off length of the regimes to be determined for variable X. The change in the confidence of a regime shift at the point when year i is equal to possible starting point j of the new regime $R2$ is reflected in the value of the regime shift index (RSI), which represents a cumulative sum of the normalized anomalies:

$$RSI_{i,j} = \sum_{i=j}^{j+m} \frac{x_i^*}{l\sigma_l}, \qquad m = 0, 1, \ldots, l\text{-}1$$

here $x_i^* = x_i - \bar{x}'_{R2}$ if the shift is up, or $x_i^* = \bar{x}'_{R2} - x_i$ if the shift is down.

The RSI value can be affected by cut-off length (*l*) and probability level (*p*) (Rodionov, 2004). The cut-off length determines the minimum length of the regimes, for which the magnitude of the shifts remains intact. I set cut-off length as 10 year and probability level as 0.05 to investigate decadal scale shifts in ocean environments and population size of jack mackerel in this study.

2.3 RESULTS

2.3.1 Variations in Ocean Environmental Conditions around Korean Waters

Physical ocean environments were examined using seawater density at surface and 50m layer depth from 157 stations over 38 years. I divided the stations using self-organizing mapping (SOM) and excluded marginal areas, which showed strong annual variability (Fig. 2-1) relative to the strength of the Kuroshio Current. Then, three distinct clusters were divided during the period of 1965-2003 around Korean waters. High variability areas red and red-like colors were larger at surface layer depth than those at 50m in each water property (Fig. 2-1 left-hand). Although spatial distribution of surface water-types was wider than that of the 50m depth-types (Fig. 2-2 left-hand), the temperature-salinity (T-S) patterns showed similar at surface and 50m layer

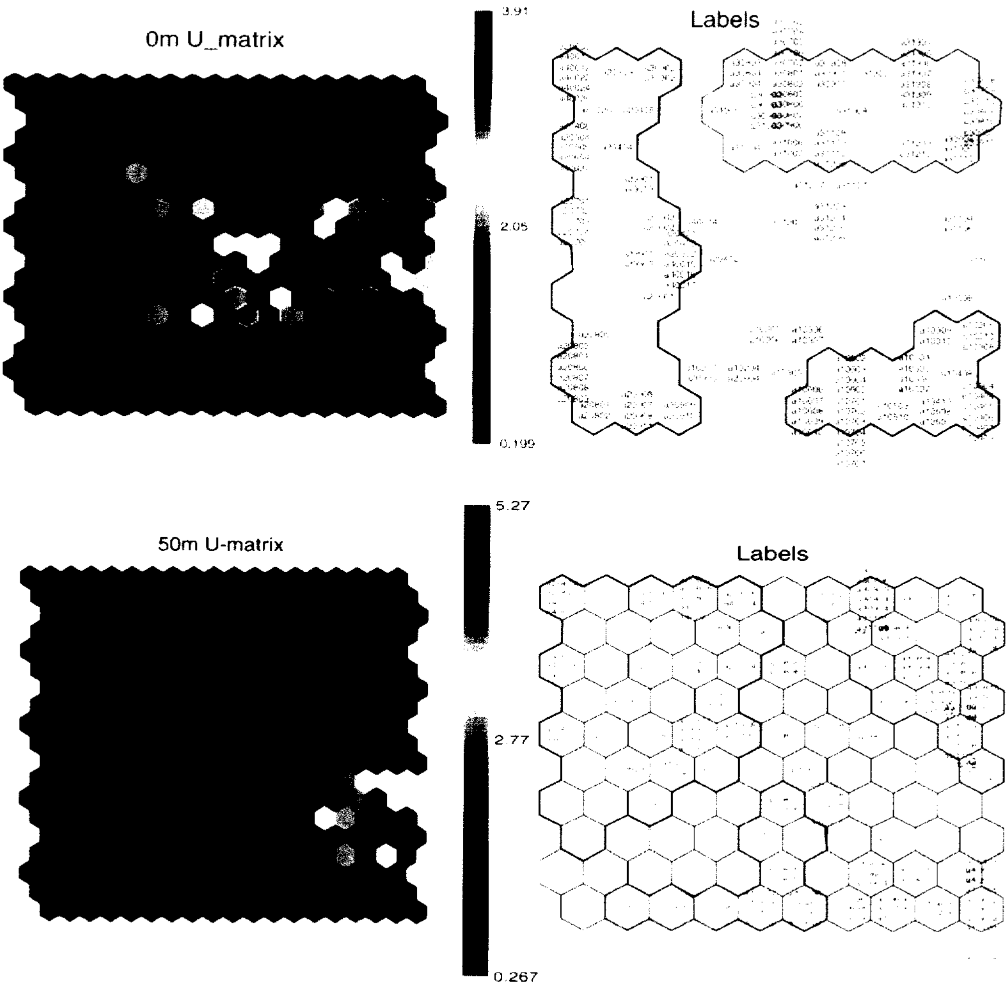

Fig. 2-1. Maps of seawater density (sigma-t) at surface (top) and 50m (bottom) layer depth by station. The color types were identified using self-organizing mapping (See text for explanation). Blue color indicate low variability and red color high variability among the oceanographic survey stations of KODC.

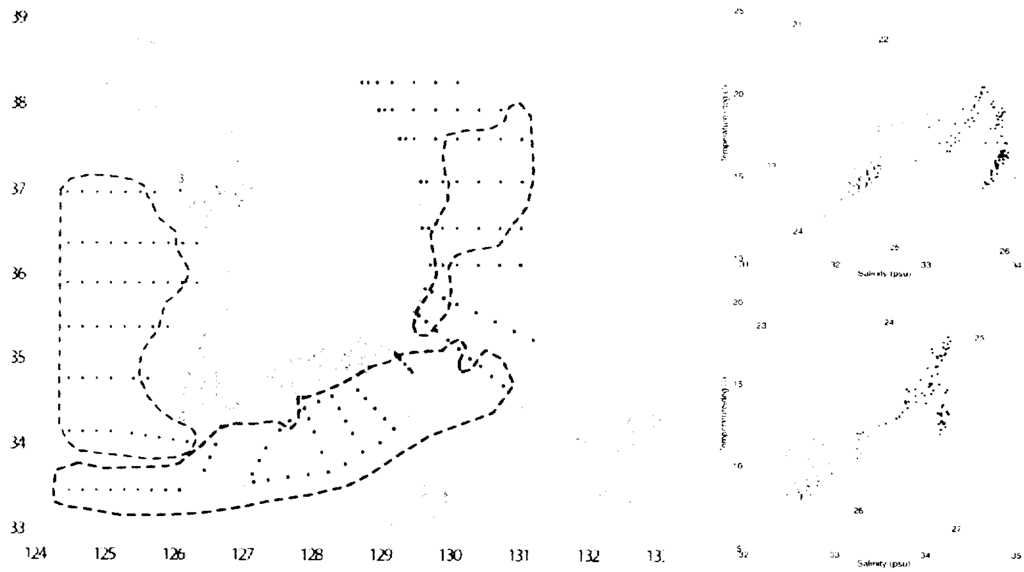

Fig. 2-2. Spatial distribution (left) and T-S diagrams at surface (right top) and 50m (right bottom) layer depth categorized water-masses with regard to density by SOM. Red color areas denote water property of Japan/East Sea, blue color that of East China Sea, and green color that of Yellow Sea of Korea.

depths (Fig. 2-2 right-hand). Therefore, three clusters of density explained water properties, corresponding to the Japan/East Sea (JES), East China Sea (ECS), and Yellow Sea (YS) of Korea. Wavelet analyses were conducted with density from three clustering areas at surface and 50m layer depth. The six wavelet spectra of three water-properties exhibited strong decadal frequencies of 8-16 years, especially global wavelet spectra at 50m layer depth of them commonly showed a peak from the late 1970s to late 1980s within 95% confidence levels (Fig. 2-3). Therefore, three water properties consisted of stations with similar annual fluctuations over 38 years showed decadal variations in Korean waters.

Ocean surface current trajectories traveling from 26°N and 123°E showed inter-annual variability from 1968 to 2004 around Korean waters (Fig. 2-4). Most surface currents drifted westwards during the 1980's, while they moved eastwards to the western area of Kyushu of Japan during 1990's. During the 38-year period of 1968-2004, the surface drifts of 16 years could reach and were sustained in the touch-down zone from April to June. The surface trajectories traveled eastward for 10 years (1969, 1974, 1977, 1981, 1983, 1991, 1993, 1994, 1996, 1998), but moved westward from the 127° E latitude

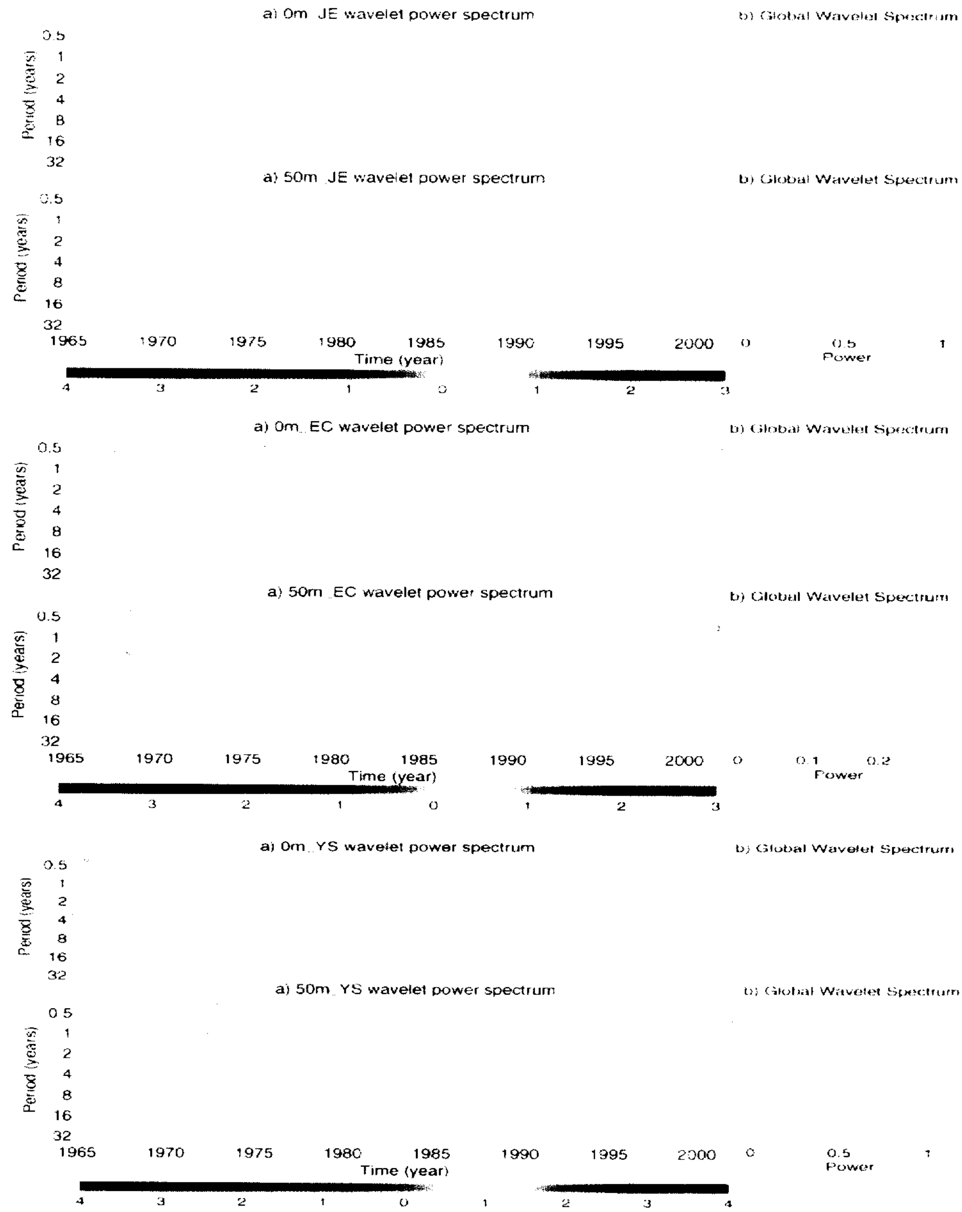

Fig. 2-3. Wavelet power and normalized global wavelet spectra at surface and 50m layer depths in Korea waters.

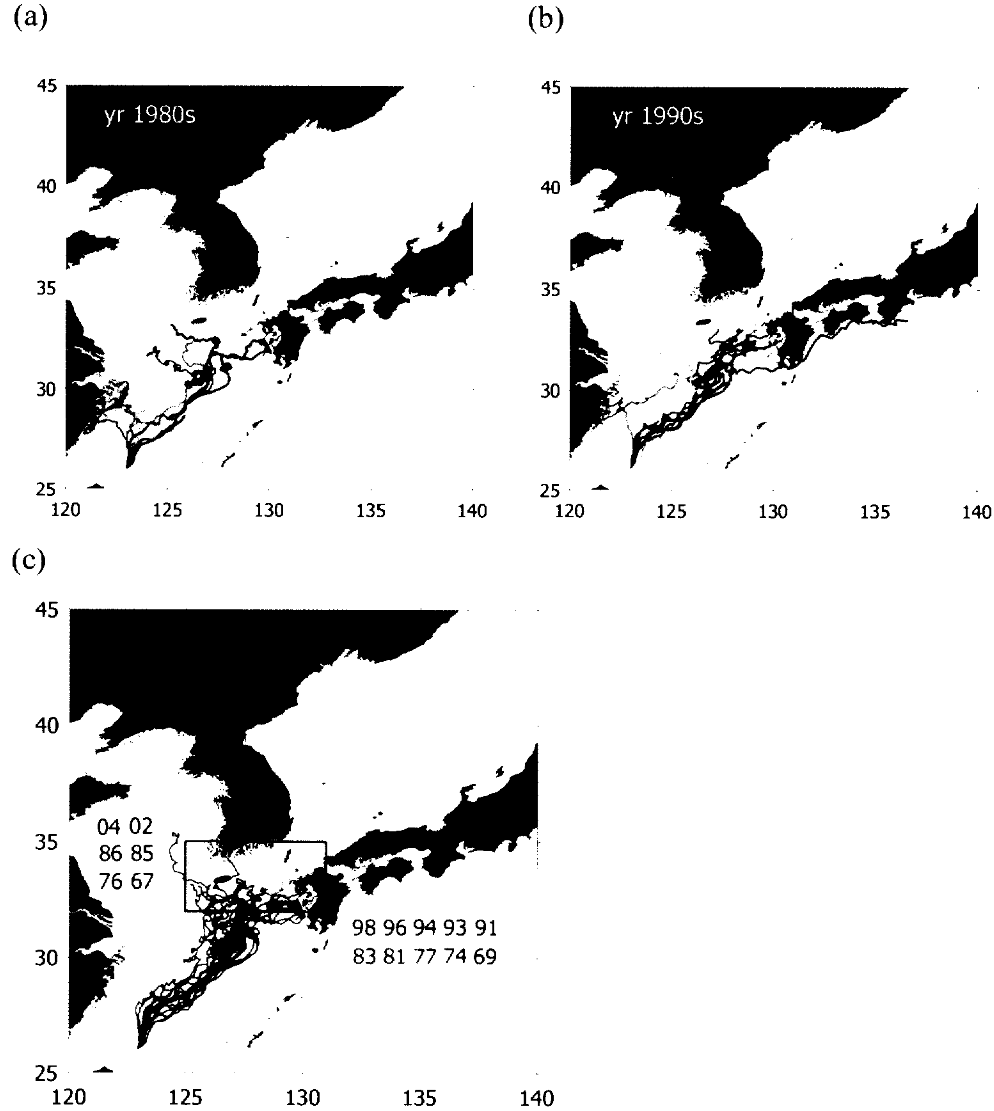

Fig. 2-4. Variations of OSCURS trajectories in (a) 1980's and (b)1990's, and (c) years when the touch down zone was successfully reached between 1968-2004. In figure (c), red trajectories indicate eastward movement and blue trajectories indicate westward movement relative to the 127° E latitude line.

line for 6 years (1967, 1976, 1985, 1986, 2002, 2004).

Zooplankton biomass at the touch down zone in the spring season was low until early 1990's, but increased significantly after early 1990's ($P<0.001$) (Fig. 2-5a). The variations in standardized zooplankton biomass in the touch down zone showed one shifts in decadal scale during the period of 1970 to 2003 (Fig. 2-5b top). The zooplankton biomass significantly increased after 1993 at $P<0.05$ (Fig. 2-5b bottom). The variation of zooplankton biomass in the touch down zone showed a significant correlation with sea surface temperature in the zone ($r=0.45$, $P<0.001$) and the 50m layer depth at the center in the catch distribution of jack mackerel ($r=0.37$, $P<0.05$) during the period of 1970-2003 (Table 2-1). The variations in standardized temperature at 50m layer depth in the touch down zone showed one shifts in decadal scale during the period of 1970 to 2003 (Fig. 2-6 top). The temperature significantly increased after 1987 at $P<0.05$ (Fig. 2-6 bottom). And the correlation between zooplankton biomass and global scale variation indices were statistically significant (with PDO, SOI, and Nino3.4 at $P<0.05$) (Table 2-1). In the period from April to June, variation in zooplankton biomass was correlated with the PDO ($r = 0.38$, $P<0.05$), with the SOI ($r= -0.43$ $P<0.05$), and with the Nino3.4 ($r=0.34$, $P<0.05$). The variation of ENSO-related indices, such as SOI and Nino3.4, showed

(a)

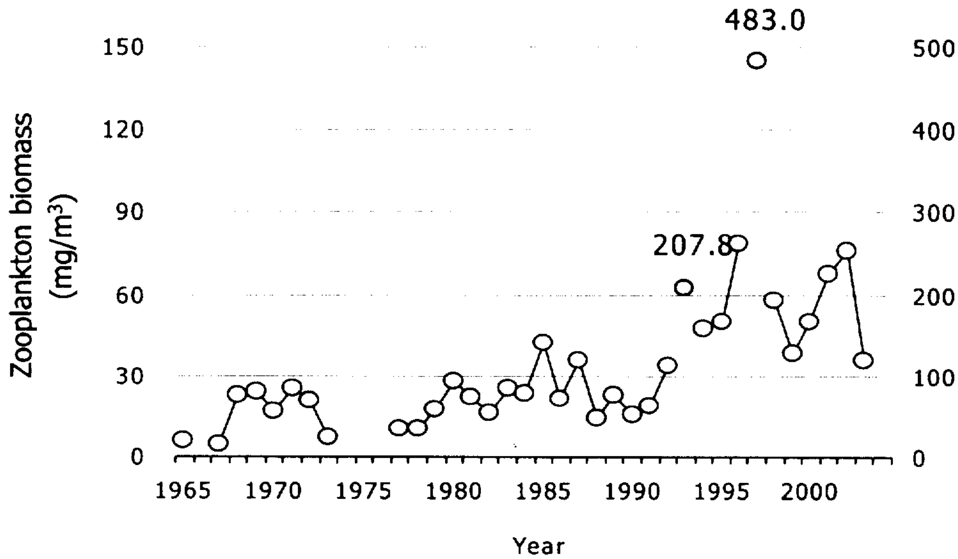

Fig. 2-5. (a) Time series of zooplankton biomass at the touch down zone during the season of April-June, 1968-2003.

(b)

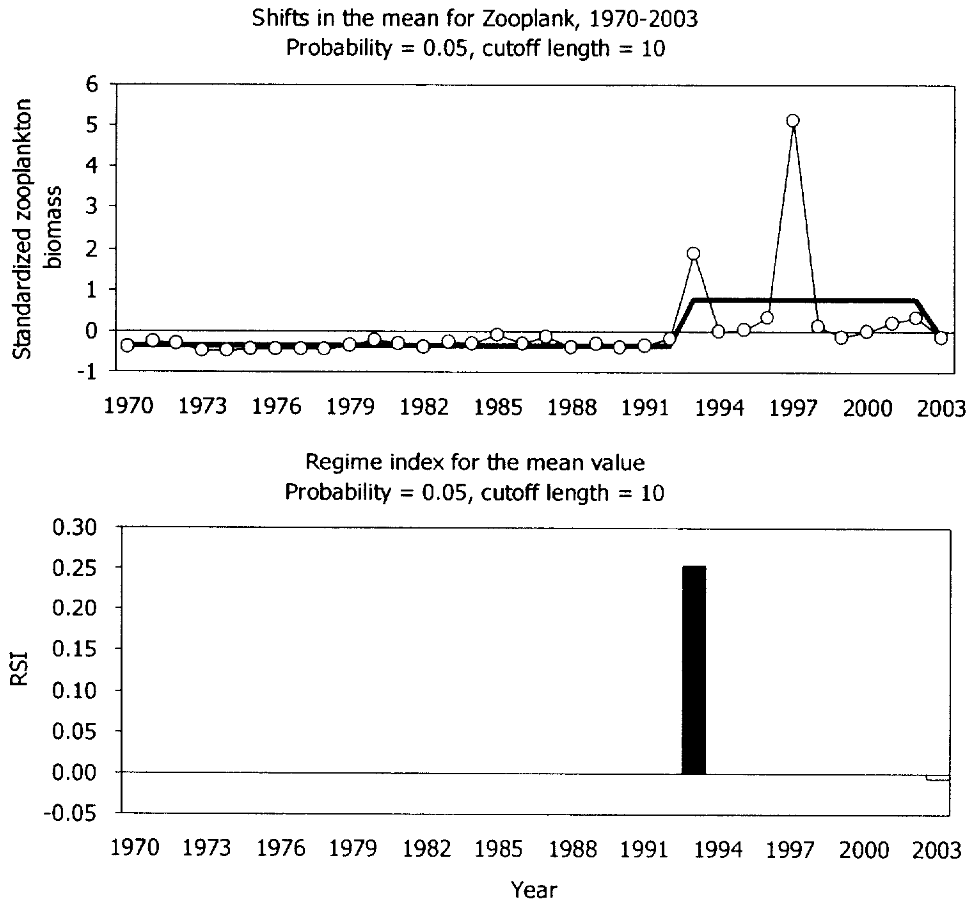

Fig. 2-5. (b) Decadal variations in standardized zooplankton biomass in the touch down zone from 1970-2003.

Table 2-1. Correlation coefficient matrix between recruitment of jack mackerel and environmental factors (**: P<0.01, *: P<0.05)

	Recruitment	Temperature	Zooplankton	PDO	SOI
Temperature	0.38*				
Zooplankton	0.45**	0.37*			
PDO	0.06	0.17	0.38*		
SOI	-0.27	-0.37*	-0.43**	-0.34*	
Nino3.4	0.23	0.35*	0.34*	0.42**	-0.83**

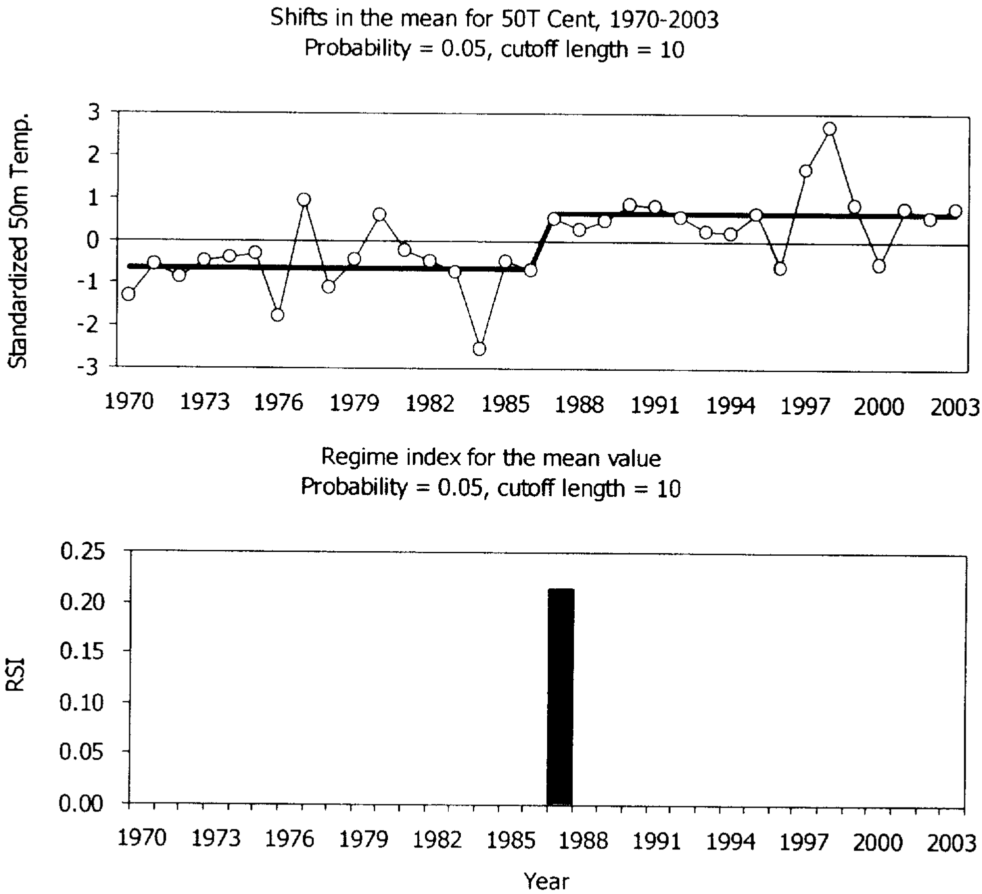

Fig. 2-6. Decadal variations in standardized temperature at 50m layer depth in the touch down zone from 1970-2003.

significant correlation with temperature at 50m depth (with SOI and Nino3.4 at $P<0.05$), and SST (with Nino3.4 at $P<0.05$).

2.3.2 Variations in the Distribution of Jack Mackerel Stock around Korean Waters

Historical catch distribution of jack mackerel was widely distributed from 25°N to upper 35°N along the continental shelf around Korean waters (Fig. 2-7). In the middle of the East China Sea, the catch distribution widespread, even in the 1970's, but scarce in the 1980's. The catch distribution of jack mackerel in the southern Japan/East Sea and Yellow Sea became more dense during 1990s.

The catch distribution of jack mackerel during 1988-2003 showed seasonality with spatial variations during the periods between December-July and August-November in Korean waters. While the first habitats were formed eastward from the longitude line of 127°30'E, the second ones were formed westward (Fig. 2-8a and b). This spatial seasonality was seen clearly in the variations of centroids in the habitat of jack mackerel (Fig. 2-8c).

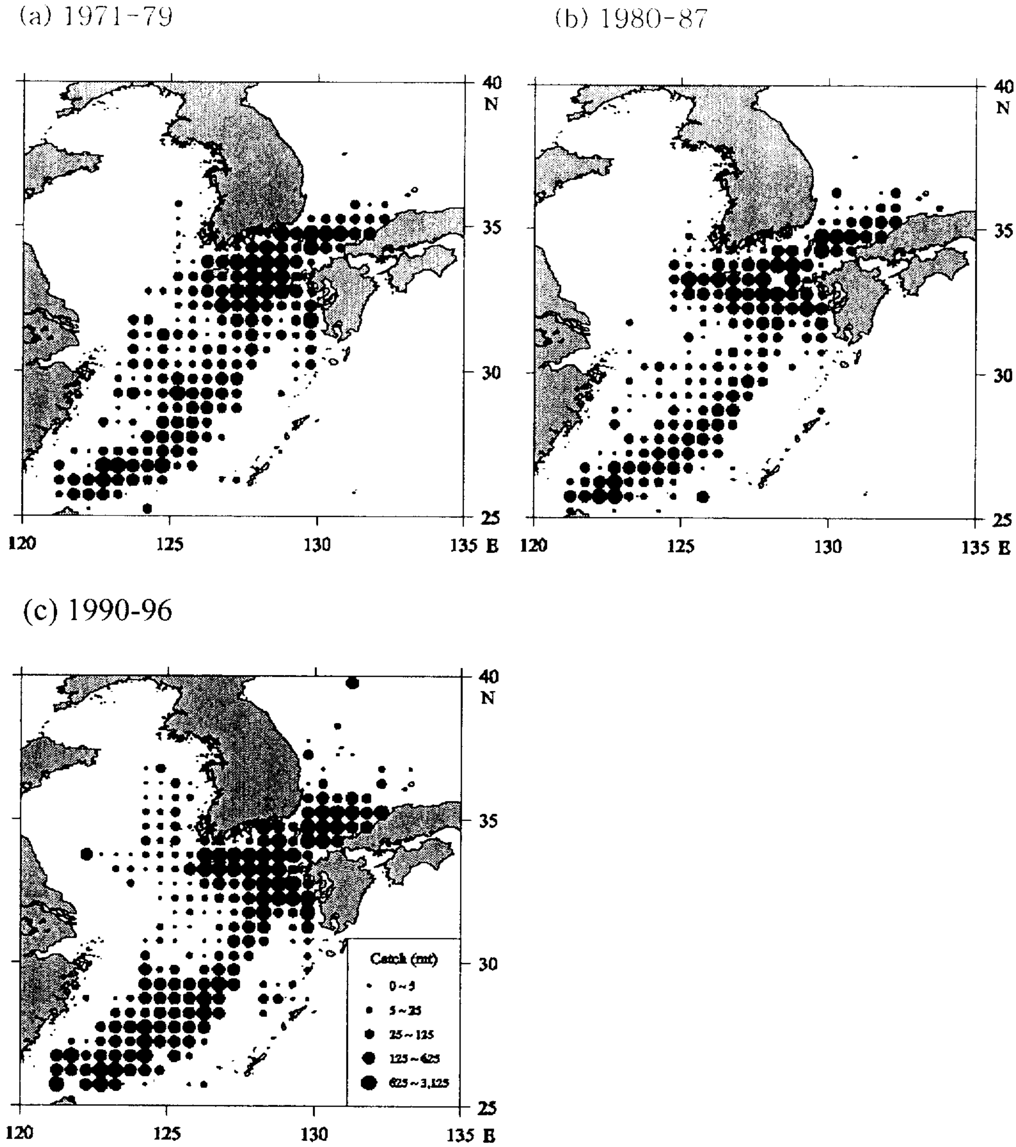

Fig. 2-7. Catch distributions of jack mackerel in the Korean and Japanese purse seine fisheries in 1970's, 1980's and 1990's.

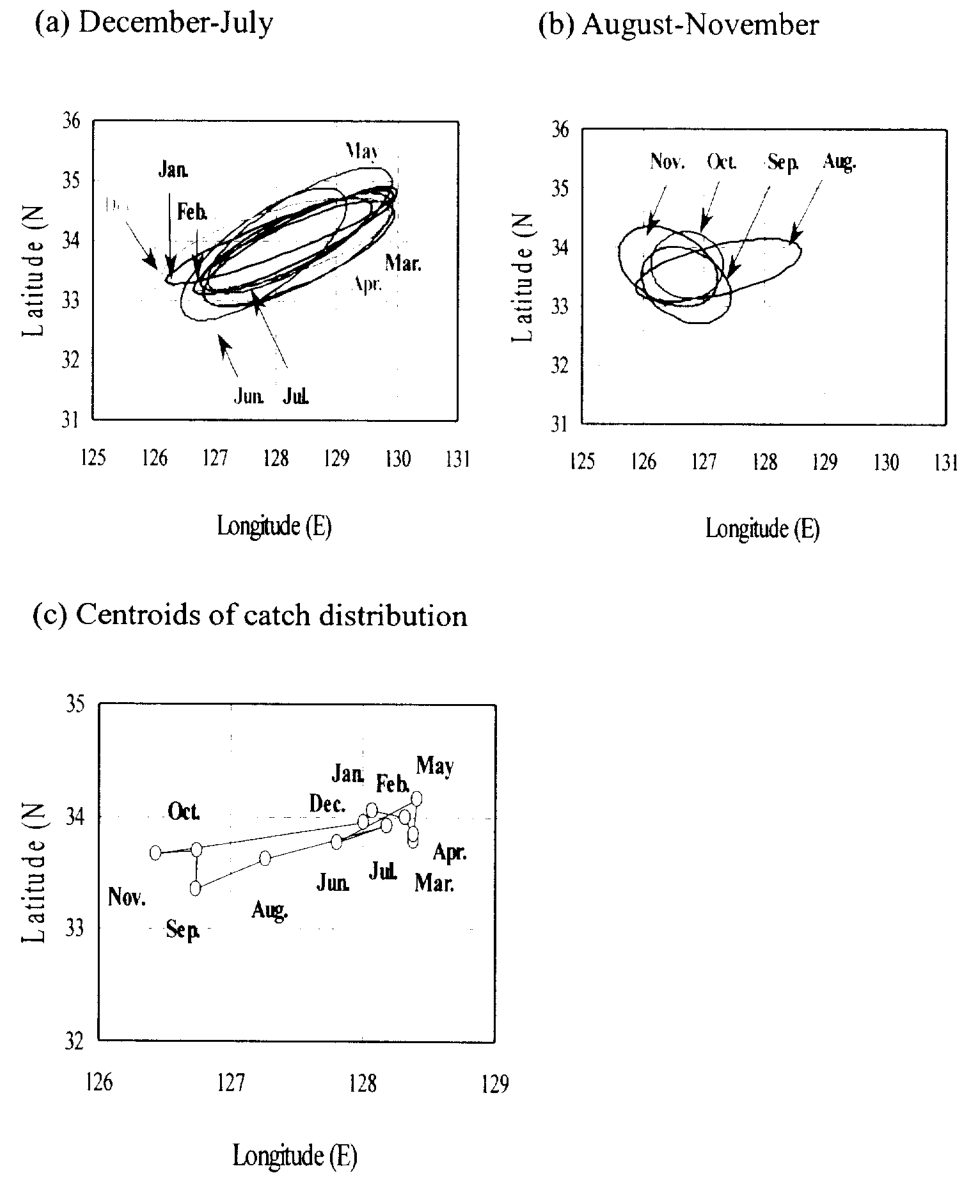

Fig. 2-8. Monthly distributions of jack mackerel in Korean waters from 1988 to 2003.

2.4 DISCUSSION

The oceanographic survey stations with similar variations for three decade in Korean waters were categorized into five groups by the self-organizing map (SOM) analysis. The five groups include water property with relatively similar variation to sea areas with strong annual fluctuation. Excluding strong annual fluctuating areas, three water properties were located in the areas of the Japan/East Sea, East China Sea, and Yellow Sea of Korea, respectively. It means that SOM can make group with similar variations in water density (sigma_t) of Korean waters. While the water properties were sustained away from different geographical distance, they showed decadal frequencies (8-16 years). Those indicated that annual variations of water properties were not influenced by the variations of the strength in the Kuroshio and Kuroshio-branch Currents, but by climate-induced variations in Korean waters. These results support the facts that decadal regime shifts were occurred in Korean waters (Zhang et al., 2000, Zhang et al., 2004).

Empirical studies of climate regime shifts typically use confirmatory statistical techniques with an *a priori* hypothesis about the timing of the shifts. The most important feature of the method used in this study may be its ability to detect a regime shift relatively early and then monitor how its magnitude changes over time. A correct interpretation of the results obtained by this method requires an understanding of how such variable parameters as the cut-off length l and probability level p can affect the RSI values. The cut-off length l determines the minimum length of the regime, for which the magnitude of the shifts remains intact.

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CHAPTER 3

VARIABILITY OF ABUNDANCE AND RECRUITMENT OF JACK MACKEREL STOCK AROUND KOREAN WATERS

3.1 INTRODUCTION

Over past 70 years, the pattern of catch has been characterized by a cyclic behavior occurring with a relatively low frequency of 30 years and a high coefficient of variation (CV) of 0.79 (Zhang & Lee, 2001). According to Zhang & Lee (2001), the spawning concentration was subjected to intense fishing pressure. The fishery yield of jack mackerel was largely dependent on the recruitment in each year, so the intensity of the present fishery present a problem for maintaining a sufficient numbers of the recruited year class until it could spawn in the next year. Although the stock was heavily fished, the stock size was sustained not only by the magnitude of spawning but also environmental factors which control the survival of larval and juvenile jack mackerel (Kim, 2002).

The objective of this chapter is (1) to estimate biomass of jack mackerel with annual weight at age using the biomass-based cohort analysis, (2) to investigate abrupt shifts in time series data of catch, recruitment and spawning biomass of jack mackerel around Korean waters for 1968-2004, (3) to examine whether the spawning biomass-recruitment relationships were influenced by regime shifts around Korean waters, and (4) to estimate recruitment of jack mackerel with their spawners and environmental factors which will be used in determining reference harvest levels, such as overfishing level and acceptable biological catch of jack mackerel in Chapter 4.

3.2 MATERIALS AND METHOD

Jack mackerel abundance during the period 1982-2004 was estimated from catches and efforts by the Korean large purse seine fisheries, using the Fisheries Resources Research (FIRR) Database in the National Fisheries Research and Development Institute (NFRDI) of Korea. Age compositions were derived from the length composition data collected from the large purse seine during 1968-2004 and age-length keys of jack mackerel in Korea waters. With these data, survival rate (S) was calculated from the slope of the catch curve or each equation of the models, and instantaneous coefficient of total mortality (Z) was transformed from the survival rate as $Z=-\ln S$. The annual instantaneous coefficient of growth at age (G_j) for 1968-2004 is calculated as the following equation:

$$G_j = \ln(\frac{W_{j+1}}{W_j})$$

where W_j and W_{j+1} are the body weight at age j and j+1, respectively.

A biomass-based cohort analysis (Zhang & Sullivan, 1988) is adopted to estimate biomass and instantaneous fishing mortality at age and by year according to the following model equations, assuming that catch is taken instantaneously at mid-year,

$$B_{ij} = B_{i+1,j+1} e^{(M-G_j)} + C_{ij} e^{\frac{(M-G_j)}{2}}$$

$$F_{ij} = \ln(\frac{B_{ij}}{B_{i+1,j+1}}) - M + G_j$$

where C_{ij} is the catch in weight at age j in year i, B_{ij} and $B_{i+1,\, j+1}$ are the biomass at age j and j+1 in year i and i+1, F_{ij} is the instantaneous coefficient of fishing mortality at age j in year i, M is the instantaneous coefficient of natural mortality, and G_j is the instantaneous coefficient of growth at age j.

The classical SRR models were used to describe a spawning biomass and recruitment relationship for jack mackerel stock around Korean waters. A multiplicative error was assumed by the fact that the variations in recruitment increased with the size of spawning biomass. Then, the Ricker (1954) model becomes,

$$R_t = \alpha S_{t-t_c} e^{-\beta S_{t-t_c}} e^{\varepsilon_t}$$

where, R_t is recruitment at year t, S_{t-t_c} represents spawning biomass at year t-t_c, ε_t is random error at year t, α is a parameter related to density-independent mortality, and β is a parameter related to density-dependent mortality. Recruitment was considered to occur at age 1 for jack mackerel, since the t_c estimate was age 0.53 from length-converted catch curve. The parameters were solved by a non-linear regression. The Beverton & Holt (1957) model with a multiplicative error is

$$R_t = \frac{1}{\alpha' + \frac{\beta'}{S_{t-t_c}}} e^{\varepsilon_t}$$

where, α' and β' are parameters. The parameters were also solved by a non-linear regression.

A generalized additive model (GAM) is a useful statistical analysis tool for exploratory analysis, which is able to identify functional relationships, suggested by the data alone, in cases where conventional linear techniques have failed (Hastie & Tibshirani, 1990). The main advantage of GAM over traditional regression methods is its capability to model non-linearities using non-parametric soothers (Daskalov, 1999). Due to this point, I used correlation and GAM to explore the best recruitment estimate of jack mackerel in relation to spawning stock biomass, ocean environmental factors, such as zooplankton biomass and temperature.

The GAM general equation is given by

$$g(m) = a + \sum_{j=1}^{p} f_j(X_j).$$

In this equation $g(.)$ is the link function, $m = E(Y)$ is the expectation of the response, and $a + \Sigma f_j(X_j)$ is a function called an additive predictor. As in generalized linear models (McGullagh & Nelder, 1989), different families of models are allowed for defining the response distribution and link function. I used a lognormal distribution, which has also been recommended in other studies (Hilborn & Walters, 1992; Myers et al., 1995), and regressed log recruitment to the predictor variables. GAM fits are illustrated using partial regression graphs showing the shape of the estimated relationship between the response and each predictor, and the partial residuals around the prediction line. GAM provides a flexible way to define the predictor function $f_i(.)$, which is analogues to the regression coefficients in linear models and can be modeled non-parametrically (Daskalov, 1999). Because non-parametric terms are fitted using scatterplot smoothers, which is a tool for summarizing the trend of a response measurement as a function of one or more predictor measurements, I used a weighted local regression smoother called *loess* (Cleveland et al., 1992). The weighted local regression smooth $s(x_0)$ using k nearest-neighbors is a number of steps (Hastie & Tibshirani, 1990):

(i) The k nearest neighbors of x_0 are identified, denoted by $N(x_0)$.

(ii) $\Delta(x_0) = \max_{N(x_0)} |x_0 - x_i|$ is computed, the distance of the furthest near-neighbor from x_0.

(iii) Weights w_i are assigned to each point in $N(x_0)$, using the *tri-cube* weight function:

$$W\left(\frac{|x_0 - x_i|}{\Delta(x_0)}\right)$$

where $W(u) = (1-u^3)^3$, for $0 \le u < 1$; otherwise, is equal to be 0.

(iv) $s(x_0)$ is the fitted value at x_0 from the weighted least-squares fit of y to x confined to $N(x_0)$ using the weights computed in (iii).

This effectively works by repeatedly smoothing the variable data, and at each iteration down-weighting points with large residuals. The degree of smoothness of the *loess* term depends on two parameters: the neighborhood span (e.g. 0.5 or 0.75 of the total number of observations) and the degree (linear or quadratic *loess*) of the weighted regression fitted locally in the neighborhood of each data point (Daskalov et al., 2003).Each model fit was evaluated through analysis of deviance using approximate F-tests and the Akaike information criterion (AIC; Akaike, 1973). The form of AIC implemented in S-plus (Chambers & Hastie, 1992) is given by:

$$AIC = Deviance + 2df\phi$$

where *df* are the effective degrees of freedom used in the fit (analogue to number of parameters in linear models) and ϕ is the dispersion parameter. AIC penalises the use of additional degrees of freedom for increasing the goodness of fit. Models are compared according to their AIC values: a better model has a lower AIC.

3.3 RESULTS

3.3.1 Variations in Abundance of Jack Mackerel

According to FAO statistics (www.fao.org/fi/statist/FISOFT/FISHPLUS.asp), catches of jack mackerel are reported by Korea, Japan and Taiwan in the Northwest Pacific Ocean (FAO area code 61). During the years of 2000-2002, mean total catch of jack mackerel was 245,638 mt. Among them, Japanese catch was occupied at 89.1%, Korean was 8.6%, and Taiwan was 2.4% in the Northwest Pacific. Because Taiwanese catch of jack mackerel was very small, only 2.4%, and had a short catch history after 1989 in the Northwest Pacific, the variations in catches of jack mackerel from Korean and Japanese fisheries in the East China, the Japan/East Sea and the Yellow Sea were examined (Fig. 3-1). The Korean and Japanese catches of jack mackerel around Korean waters were significant correlated ($r=0.518$, $P<0.001$), but the Korean catch showed

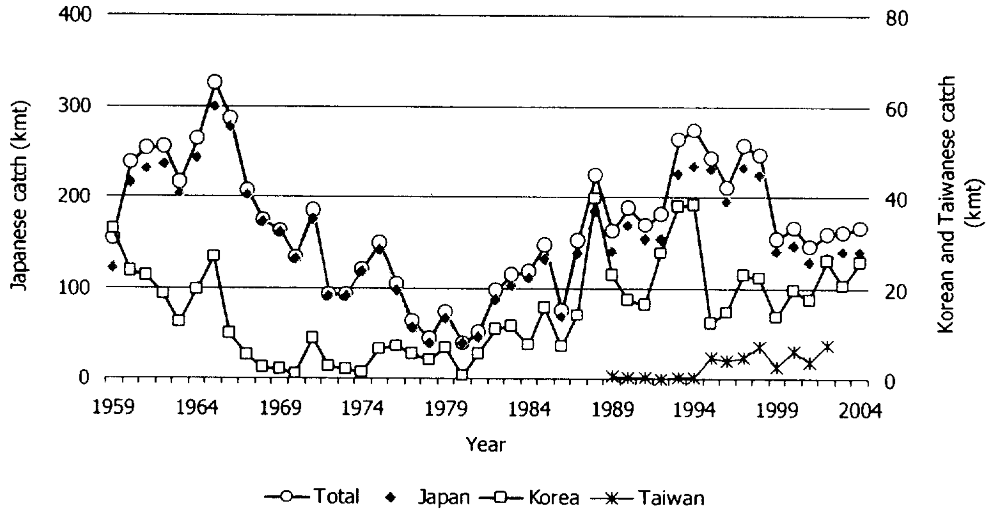


Fig. 3-1. Catches of jack mackerel around Korean waters. The total catch summed up Korean annual and Japanese Tsushima stock catches of jack mackerel. Taiwanese catch was from area 61 of FAO statistics.

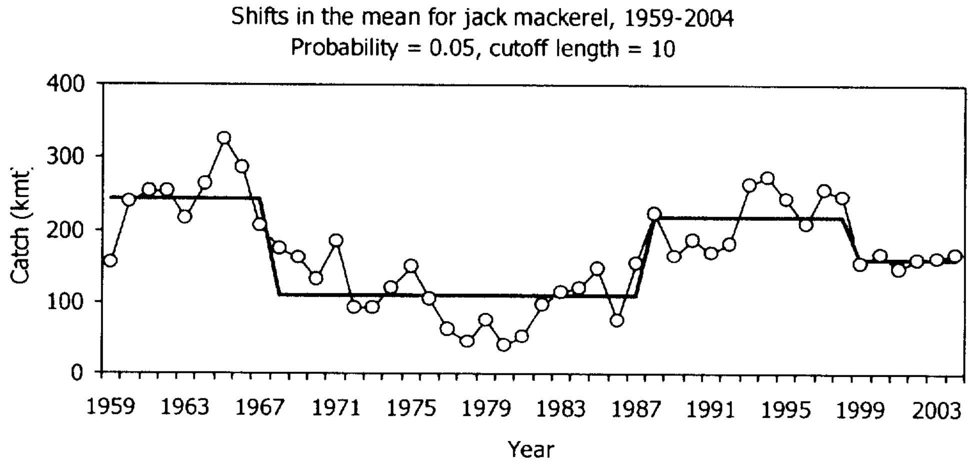
larger variations than the Japanese during 46 years (CV's: 70.4% for Korea, 41.8% for Japan) (Table 3-1). The largest annual Korean catch of jack mackerel was 48,361 mt in 1956. Subsequently the catch declined to less than 10,000 mt in the late 1960's and remained at a low level until the early 1980's. In the early 1980's, the annual catch increased and reached at about 23,000 mt in recent years (Fig. 3-1).

The variations in total catches of jack mackerel showed three shifts in decadal scale during the period of 1959 to 2004. The total catches significantly decreased after 1968 and increased after 1988 with little decline after 1999. The regime shift indices of both years (1968 and 1988) exhibited similar values at $P<0.05$ and the cutoff length of 10 years (Fig 3-2).

There was also seasonal variation in the annual catch of jack mackerel. From 1988 to 2002 catches during the two spring season months (April and May) made up about 25% of the annual catch. The percentage of catches in the fall season (September and October) was about 16% (Fig. 3-3a). During the 14-year period from 1988-2002, the total annual catch of jack mackerel in Korean waters was over 20,000 mt approximately every 2 years (that is, in 1988-1989, 1992-1994, 1997-1998, 2002). In those years the spring catch exceeded 6,000 mt in April and May, except for 1989 and 1997, when the fall catch exceeded 6,000 mt in September and October (Fig. 3-3b).

Table 3-1. Coefficient of variation and correlation between Korean and Japanese catches from 1959-2004 around Korean waters

	Variation			Correlation		
	$\bar{X}$	SD	CV	Korea	Japan	Overall
Korea	14978	10543	70.4	1.000		
Japan	153602	64203	41.8	0.518	1.000	
Overall	168581	70249	41.7	0.624	0.992	1.000



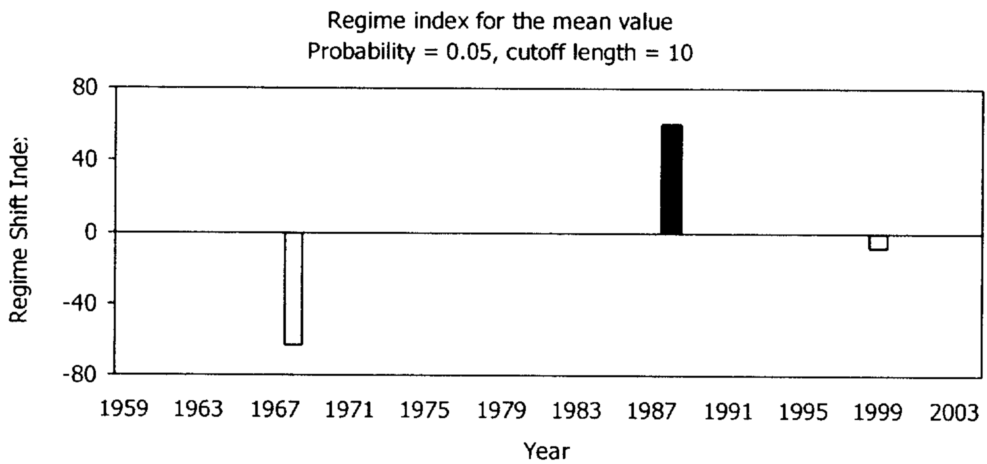
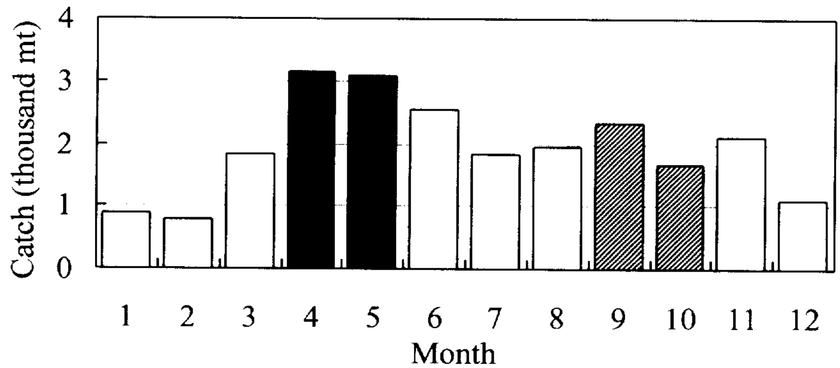


Fig. 3-2. Decadal variations in total catches of jack mackerel from 1968-2004 around Korean waters.

(a)



(b)

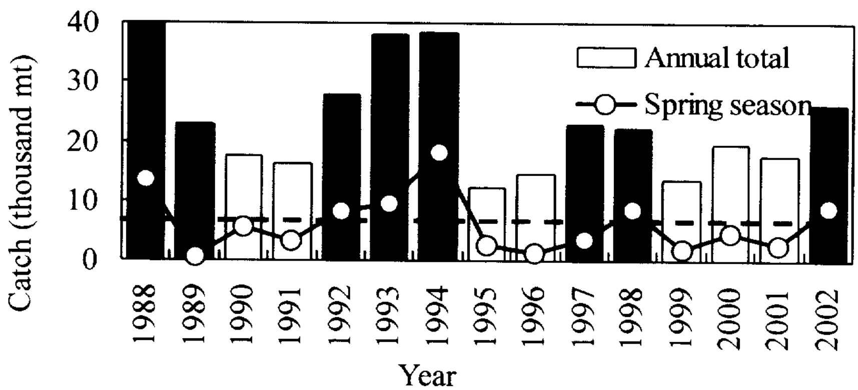


Fig. 3-3. Monthly and annual catches of jack mackerel in Korean waters. (a) Monthly catches in April and May (black bar) were about 25%, and those in September and October (lined bar) were about 16% of annual total catch from 1988 to 2002. (b) Catch in spring season over 6,000 mt (dotted line) determined annual total catch over 20,000 mt (red bar) from 1988 to 2002, except of 1989 and 1997.

Using the slope of the catch curve, instantaneous coefficient of total mortality (Z) was estimated to be 1.23/year, and the survival rates were transformed to 0.29. The estimate (0.57/year) of instantaneous coefficient of natural mortality with the instantaneous coefficients of total mortality (1.23/year) provided estimates of the instantaneous coefficient of fishing mortality at 0.65/year. The age at first capture (t_c) was determined to be age 0.83 from the length-converted catch curve of the Pauly (1984) method and the recruitment age was assumed as age 1 in this study.

To evaluate the effect of variability in estimated total mortality rates (1.23/year) on stock assessment of jack mackerel, I calculated biomass and recruitment of horse mackerel from the biomass-based cohort analysis using instantaneous coefficients of fishing mortality (0.65/year). Average in the estimate of biomass with F was 516,530 mt (SE=31,658) during the period of 1968-2004. Average in the estimate of recruitment, biomass at age 1 was 172,939 mt (SE=12,227) during the same period. Biomass and recruitment of jack mackerel were not highly influenced by the difference between the constant and annual weight at age.

The variations in mean-weight-at-recruit-age showed three shifts in decadal scale during the period of 1968 to 2004. The mean weight of recruits decreased after 1981 and increased after 1992. In recent years, the mean weight at age decreased again. The regime shift index of year 1992 was the highest among the three shift points at $P<0.05$ and the cutoff length of 10 year (Fig. 3-4).

In the biomass-based cohort analysis, the annual weight at age from annual length-weight relationships for 1968-2004 were used to estimate biomass of jack mackerel around Korean waters. The biomass and instantaneous fishing mortality with the constant weight at age calculated from von Bertalanffy growth parameters and mean length-weight relationship were underestimated in comparison of those with annual weight at age, especially when the biomass was high, the bias was higher (Fig. 3-5).

The variations in total biomass of jack mackerel showed two shifts in decadal scale during the period of 1968 to 2004. The total biomass significantly decreased after 1976 and increased after 1987. The regime shift indices of both years exhibited similar values at $P<0.05$ and the cutoff length of 10 year (Fig. 3-6). The variation in recruitment of jack mackerel showed two shifts in decadal scale with the same shift patterns as that in biomass during the period of 1968 to 2004, that is, the recruitment decreased significantly after 1974 and

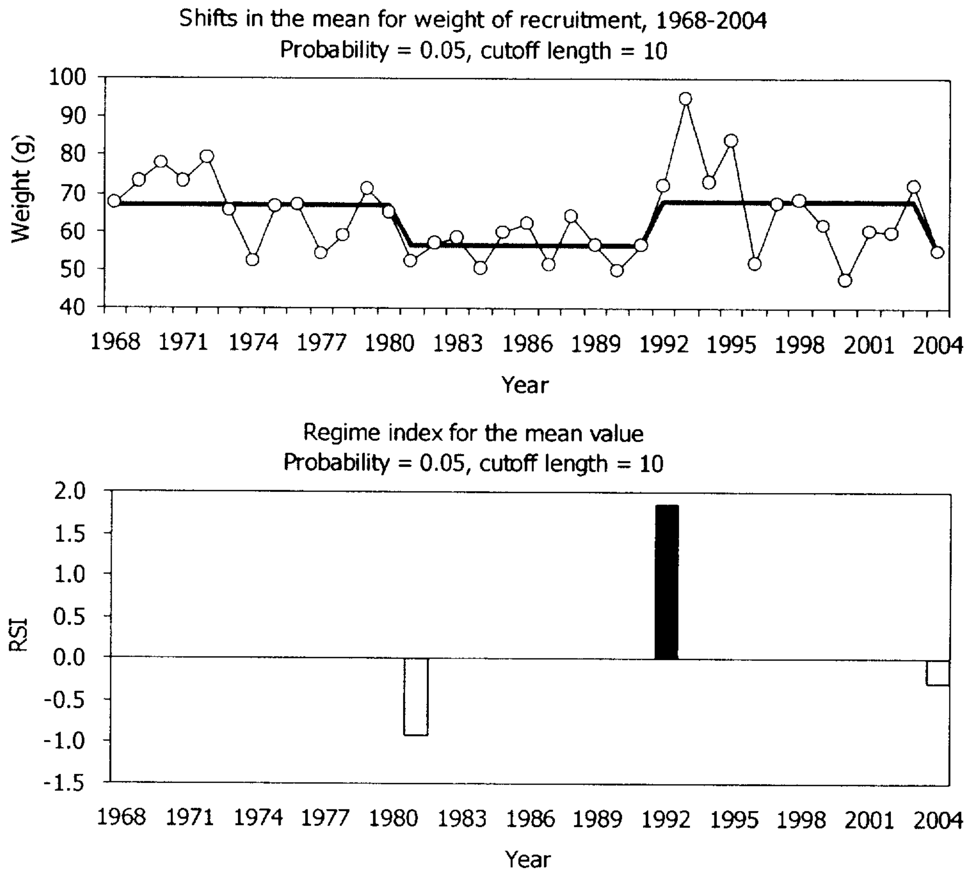
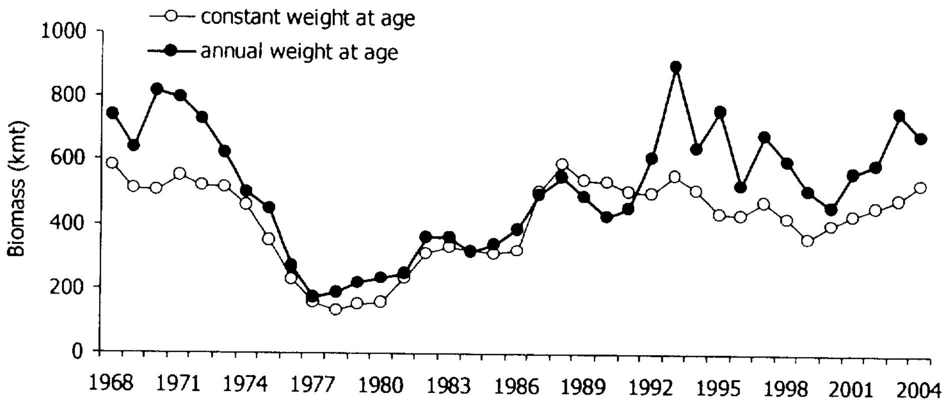


Fig. 3-4. Decadal variations in mean weight at recruit age of jack mackerel from 1968-2004 around Korean waters.



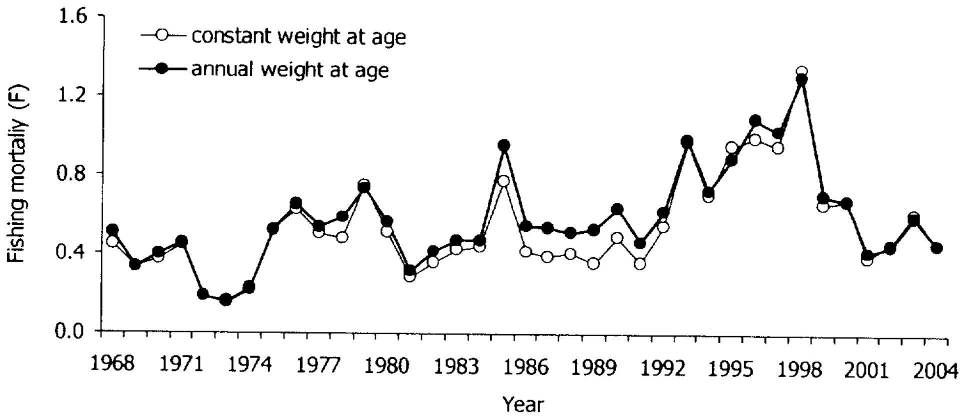


Fig. 3-5. Comparison of biomass (upper) and fishing mortality (down) estimates from the biomass-based cohort analysis with between constant and annual weight at age for 1968-2004.

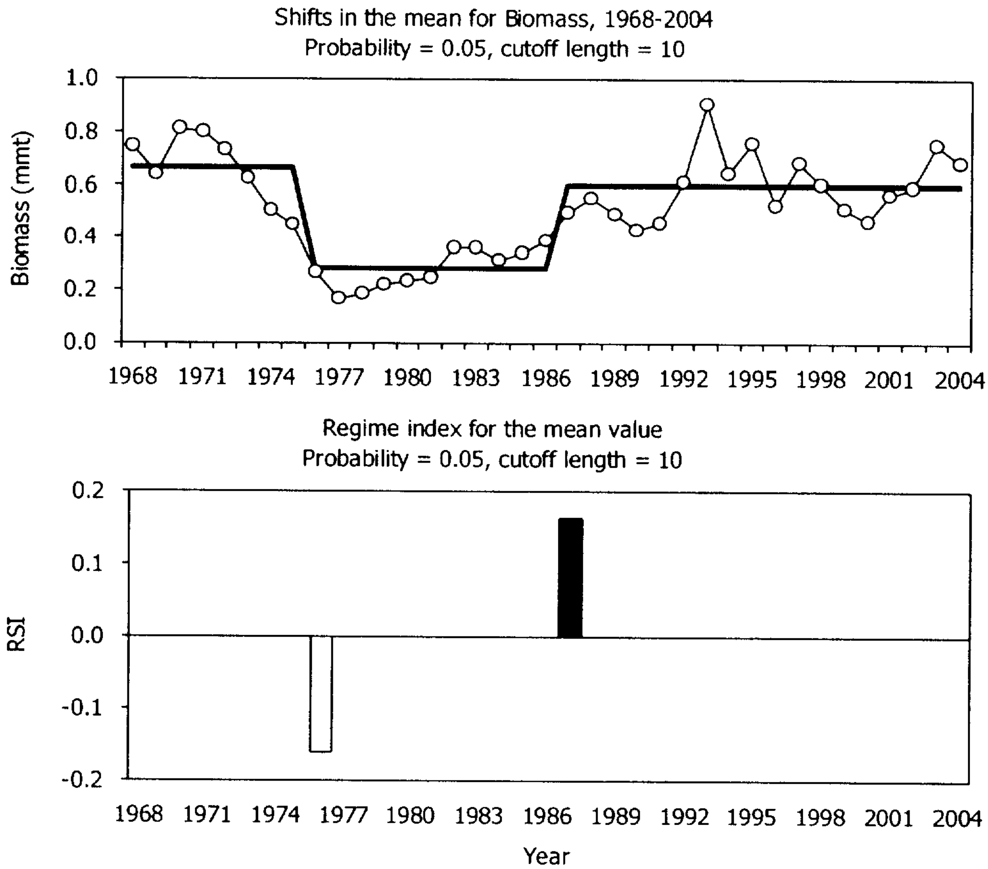


Fig. 3-6. Decadal variations in total biomass of jack mackerel from 1968-2004 around Korean waters.

increased after 1987. The regime shift index for the year 1987 was higher at P<0.05 and the cutoff length of 10 year (Fig. 3-7). The variations in spawning biomass of jack mackerel showed two shifts in decadal scale during the period of 1968 to 2004. The spawner biomass decreased significantly after 1976 and increased slightly after 2002. The regime shift index of year 1976 was higher at the same discontinuity test conditions as recruitment, while the mid 1980's regime shift was not existed in the variation of spawning biomass around Korean waters (Fig. 3-8).

3.3.2 Variations in Spawner and Recruitment Relationship of Jack Mackerel

The relationship between spawning stock biomass and recruitment of jack mackerel showed an extreme annual variability (Fig. 3-9). Neither the Ricker nor Beverton-Holt curves provided a satisfactory description of the stock-recruit relationships during the pooled period of 1968-2004. During the period of 1968-2004, significant shift points occurred in 1976 and 1987 (Fig. 3-10). Based on the times of the two shift points, I examined subsets of the data using three periods (1969-1976, 1977-1986, and 1987-2004) (Fig. 3-9). During the periods of 1969-76 and 1987-2004, the linearized Ricker and Beverton-Holt

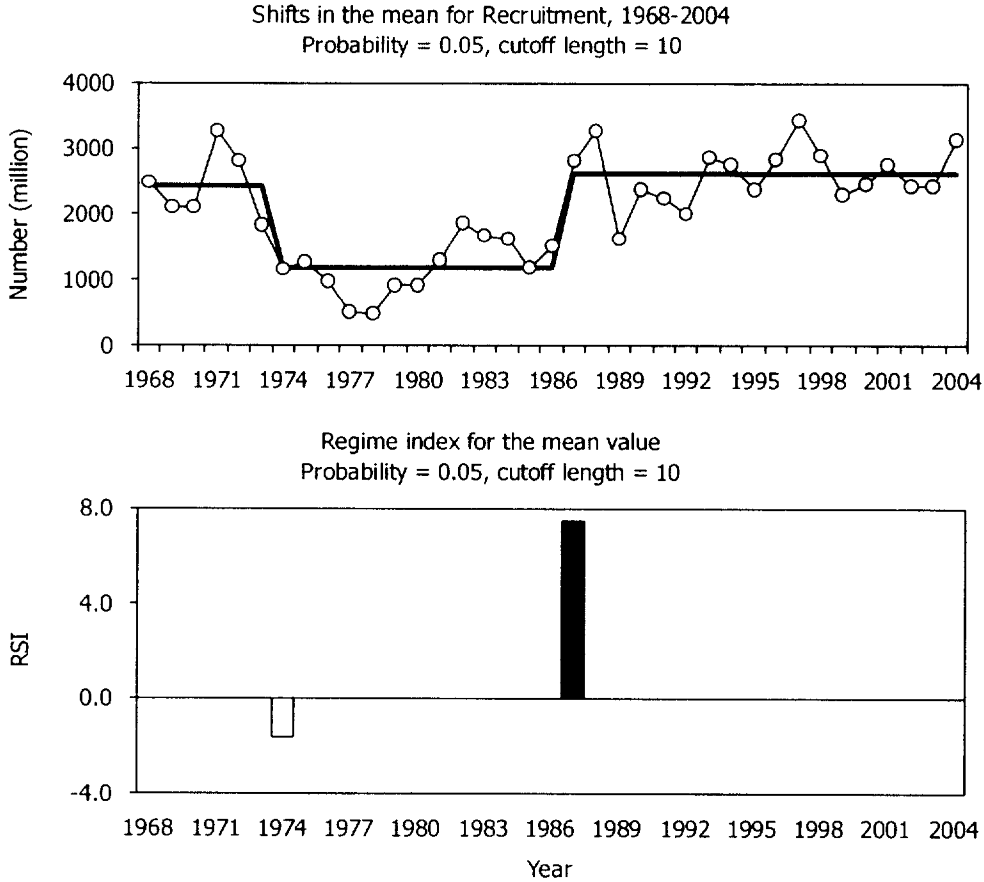


Fig.3-7. Decadal variations in recruitment of jack mackerel from 1968-2004 around Korean waters.

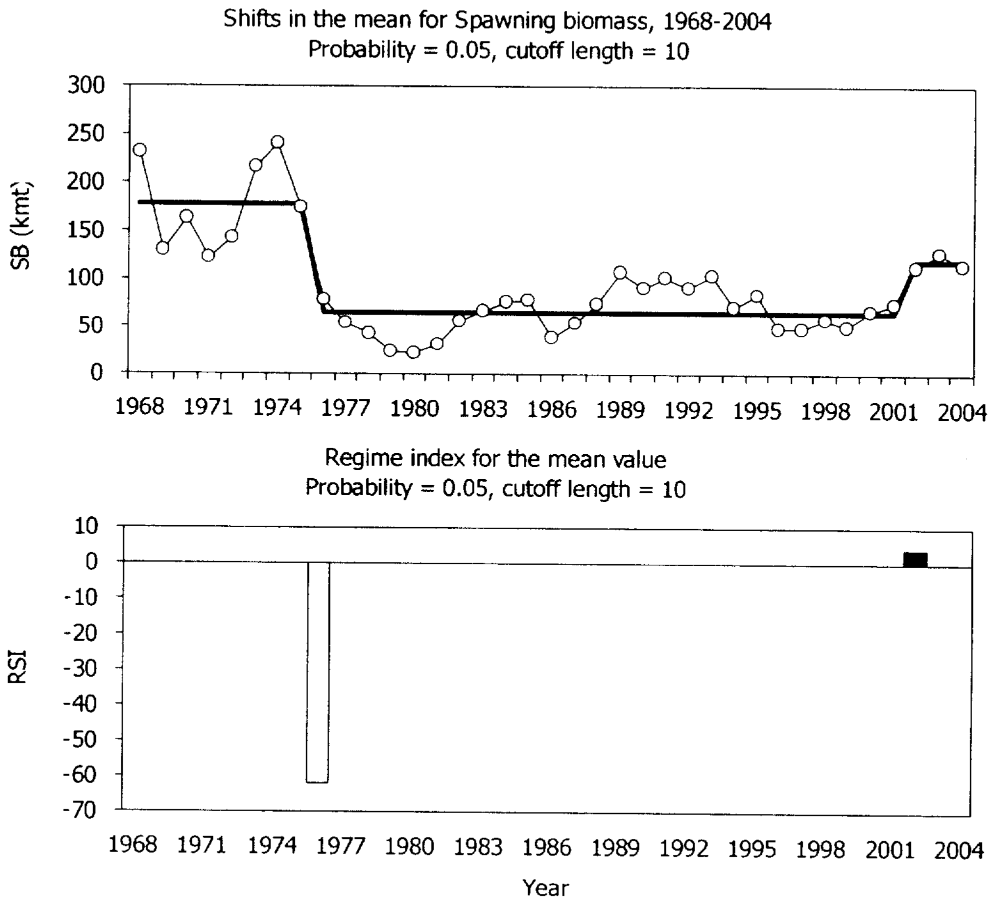


Fig. 3-8. Decadal variations in spawning biomass of jack mackerel from 1968-2004 around Korean waters.

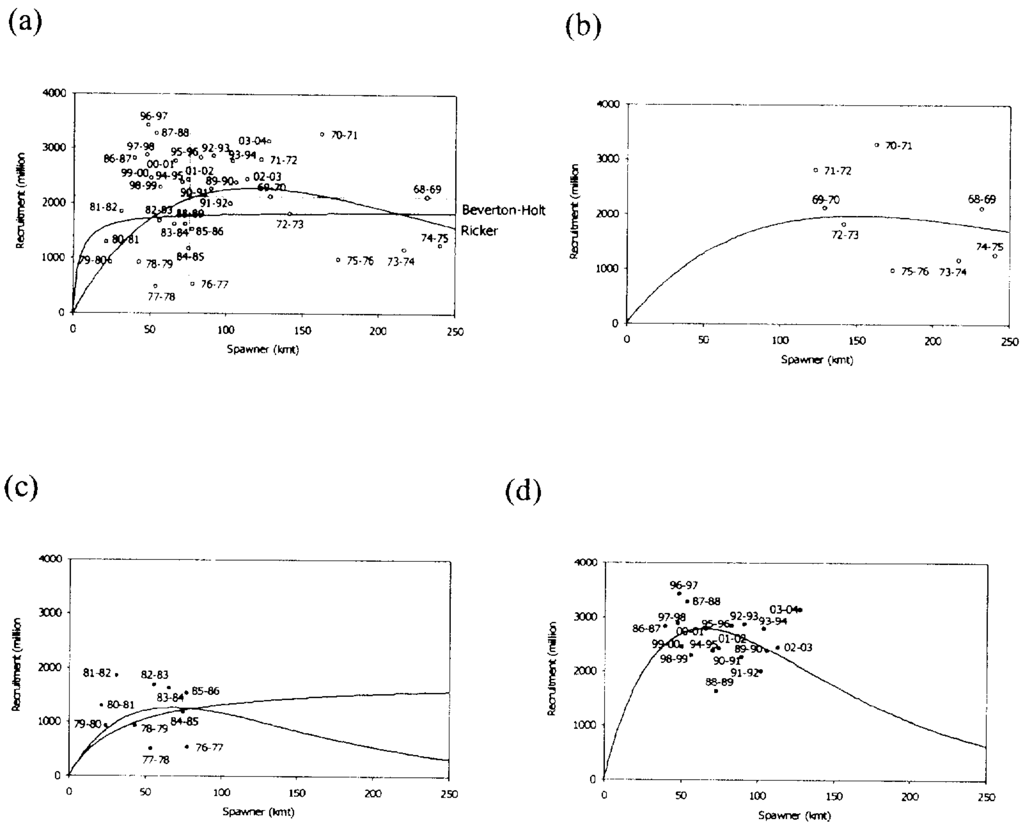


Fig. 3-9. Spawning biomass and recruitment relationships of jack mackerel during the periods of (a) 1969-2004, (b) 1969-1976, (c) 1977-1986, and (d) 1987-2004.

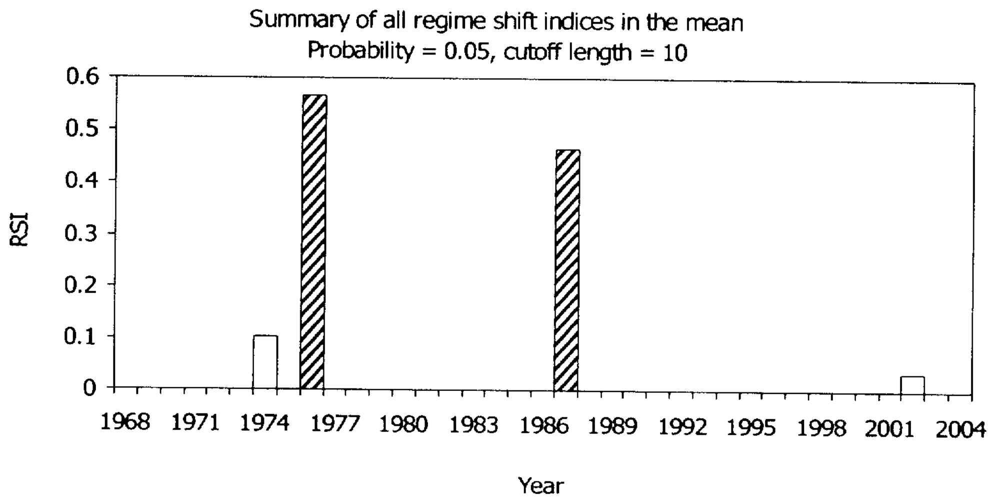


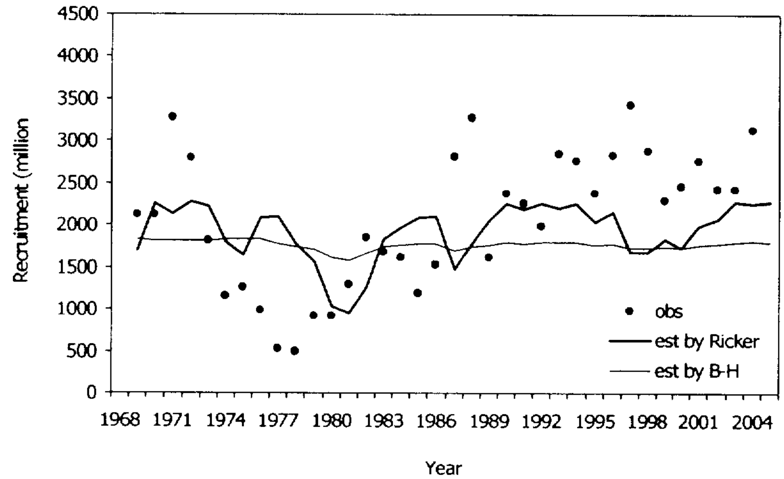
Fig. 3-10. Regime shift index pooled with standardized spawning biomass and recruitment of jack mackerel for 1968-2004. RSI values were larger than 0.4 in the years of 1976 and 1987, which indicating with shaded bars. The regime shift year of 1976 explained shift of spawning biomass, and the year of 1987 explained drastic change of recruitment of jack mackerel around Korean waters.

functions did not provide fit to the relationships at P<0.05. During the period of 1977-1986, both the Ricker and Beverton-Holt functions provided a fit to the spawner stock and recruitment data at P<0.05. Based on the density-dependent and density-independent parameters during each period, I estimated recruitment using Ricker and Beverton-Holt models. With one regime ($\alpha = 52.3$, $\beta = 0.008$ for Ricker curve, $\alpha = 473.5$, $\beta = 0.253$ for Beverton-Holt curve), recruitment of jack mackerel was significantly correlated with the recruitment estimates by Ricker model (P<0.05), but not with the Beverton-Holt model (Fig. 3-11a). On the other hand, considering three regimes, spawner-recruit relationship were very significant (Fig. 3-11b, Table 3-2).

3.3.3 Spawner and Recruitment Relationships of Jack Mackerel Incorporating Environmental Factors

GAM models were developed to explore relationships between jack mackerel recruitment, spawning biomass, and mean temperature and zooplankton biomass as environmental variables in the touch down zone. Six fitted models of log recruitment, as a function of log spawning biomass, and environmental variables are presented in Table 3-3. Adding environmental variables improved the model fit with higher correlation coefficient and lower AIC

(a)



(b)

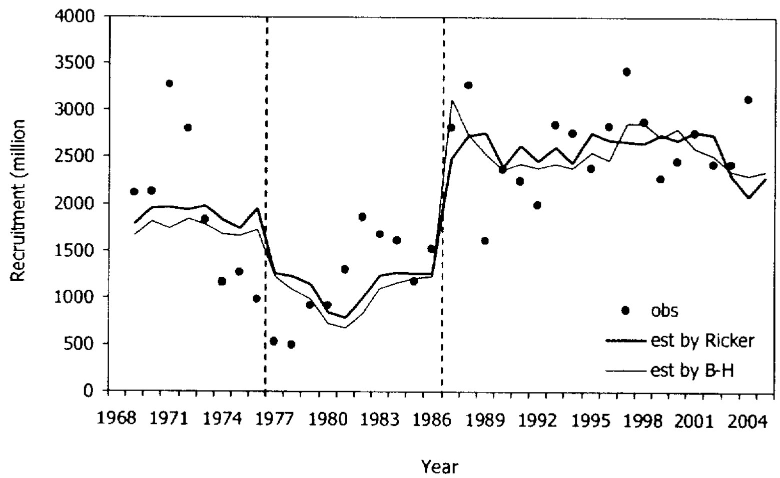


Fig. 3-11. Ricker and Beverton-Holt stock and recruitment relationship and fitted curves of jack mackerel around Korean waters during the period of (a) 1969-2004, and (b) 1969-1976, 1977-1986, 1987-2004, respectively.

Table 3-2. Results of correlation analyses for comparing observed and estimated recruitment of jack mackerel around Korean waters by Ricker and Beverton-Holt stock-recruitment models with one regime and three regimes (* n/s denotes 'not significant')

	One regime		Three regime	
	Ricker	B-H	Ricker	B-H
r	0.289	0.171	0.721	0.730
P-value	<0.05	n/s*	<0.001	<0.001

Table 3-3. Analysis of deviance of the fitted generalized additive model (GAM) with 34 year data. Intercepts and linear coefficients are omitted in accordance to the S-plus© notations (* df denotes 'degree of freedom', ** AIC means 'Akaike information criterion')

Models		Residual df*	Deviance	AIC**	r^2
n =	34				
null deviance =	8.225352				
Response:	lnR				
1	lnS	32	7.582805	71.582805	0.07811785
2	lo(S,T,Z)	30.16629	5.540422	65.873002	0.3438695
3	lnS+lo(T,Z)	30.30316	5.37722	65.98354	0.35037687
4	lo(S,T)	31.27268	6.803467	69.348827	0.20475272
5	lo(S,Z)	24.78117	3.243098	52.805438	0.60615904
6	lnS+lo(Z)	27.07558	3.223686	57.374846	0.60935906

values (Table 3-3). In Table 3-3, the goodness of the fit of models was evaluated accounting for degrees of freedom used with null deviance of 8.22. The weighted local regression smoother (called *loess*) between log recruitment versus spawning biomass and log recruitment versus zooplankton biomass had better fits and a lower AIC value (52.80) than regressions based only on spawning biomass without environmental variables. The best model, in terms of AIC, was model 5 with lowest AIC of 52.80, although model 6, in which log recruitment was regressed against log spawning biomass plus *loess* zooplankton biomass, had the highest r^2 of 0.609, (Table 3-3). The time-series of estimated recruitment by GAM in model 5 (*loess* of spawning biomass and zooplankton biomass) provides a good explanation for the period from the early 1970's to the early 1980's and then from the mid-1990's and later. The estimated recruitment by GAM model 5 in Table 3-3 did not explain the variability of observed recruitment before 1973 or during the period of 1987 to 1994. The 1993 recruitment estimate was especially high - about twice the actual recruitment of jack mackerel (Fig. 3-12).

During the recent regime after 1988, the GAM with 15 year data were developed to explore relationships between jack mackerel recruitment, spawning biomass and environmental variables, here zooplankton biomass in the touch down zone and Pacific Decadal Oscillation (PDO). Fitted models of

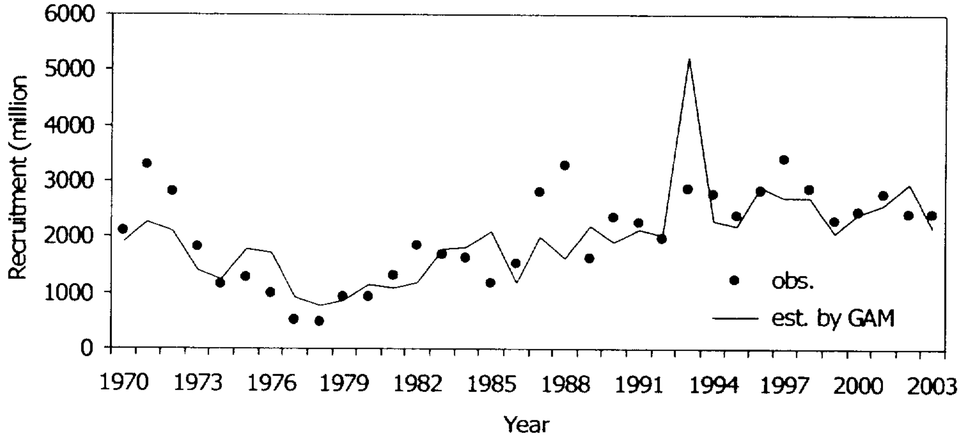


Fig. 3-12. Observed and estimated recruitments of jack mackerel based on spawning biomass and zooplankton biomass around Korean waters using GAM model 5 in Table 3-3.

log recruitment as a function of log spawning biomass and environmental variable are shown in Table 3-4. Adding environmental variables improved the model fit with higher coefficient of determination and lower AIC value (Table 3-4). The goodness of the fit of models was evaluated accounting for degrees of freedom used with null deviance of 0.44. The *loess* between spawning biomass, zooplankton biomass and PDO had best fit with lowest AIC of 8.11 and highest r^2 of 0.89 among seven model with combination of the variables (Table 3-4). The time-series of estimated recruitment by GAM model 2 (loess of spawning biomass, zooplankton biomass and PDO) provided the best explanation for the period of 1989-2003 (Fig. 3-13).

3.4 DISCUSSION

The spawning biomass-recruitment relationships were divided into 4 different situations: (i) good recruitment and good spawner, (ii) good recruitment and bad spawner, (iii) bad recruitment and good spawner, and (iv) bad recruitment and bad spawner conditions. The SRR are not variations in only recruitment or only spawning biomass, therefore the discontinuity in the relationship of pooled recruitment and spawning biomass of jack mackerel was tested during

Table 3-4. Analysis of deviance of the fitted generalized additive model (GAM) with 15 year data. Intercepts and linear coefficients are omitted in accordance to the S-plus© notations (* df denotes 'degree of freedom', ** AIC means 'Akaike information criterion')

Models		Residual df*	Deviance	AIC**	r^2
n =	15				
null deviance =	0.4380993				
Response:	lnR				
1	lnS	13	0.3159742	26.3159742	0.27876109
2	lo(S,Z,Pdo)	4.030774	0.0485814	8.1101294	0.89395129
3	lnS+lo(Z,Pdo)	4.604726	0.0529183	9.2623703	0.87938396
4	lo(S,Z)	5.201238	0.1085168	10.5109928	0.76024637
5	lo(S,Pdo)	5.604726	0.0560394	11.2654914	0.8721641
6	lnS+lo(Z)	7.637916	0.124454	15.400286	0.71700909
7	lnS+lo(Pdo)	9.224373	0.1338425	18.5825885	0.70871962

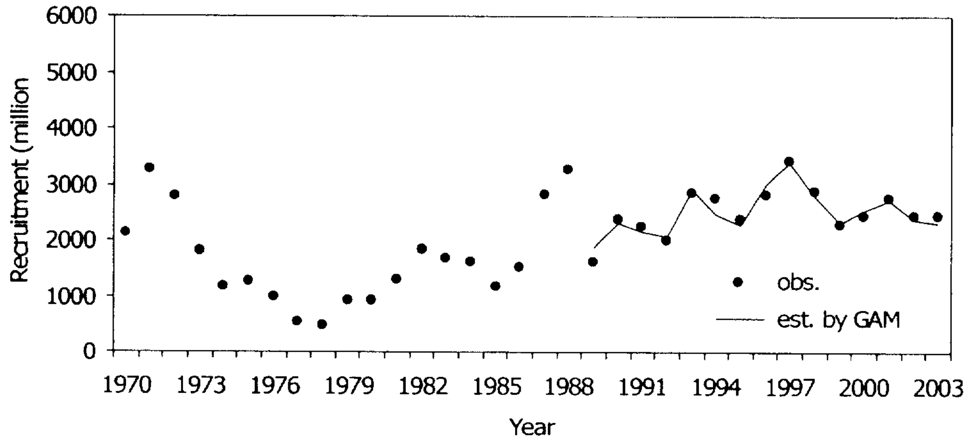


Fig. 3-13. Observed and estimated recruitments of jack mackerel based on spawning biomass, zooplankton biomass and PDO around Korean waters using GAM model 2 in Table 3-4.

the period of 1968-2004 in order to explore whether the spawner-recruit relationship of jack mackerel abruptly shifted, and if so, when the regime shifts were occurred around Korean waters.

GAMs are useful for recruitment estimation with environmental factors because nonlinear relationships among variables are allowed and effects of environmental factors on recruitment are estimated with AIC and deviance difference. GAM showed that variation in recruitment of jack mackerel was related from variations in spawning biomass, zooplankton biomass and temperature in the main habitat areas around Korean waters.

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CHAPTER 4

OPTIMAL HARVEST RATE AND HARVEST CONTROL RULES

4.1 INTRODUCTION

When the management objective on exploited fish species is to conserve and manage at the level of sustainable maximum yield (MSY), then an acceptable biological catch (ABC) should be a good candidate to be recommended. The ABC should represent an appropriate harvest rate that is applied to a current fish stock size estimate (Zhang & Marasco, 2003). Ideally, the ABC will produce a biologically acceptable average yield over a long term and avoid overfishing during periods when the stock abundance is low. The F_{MSY} (instantaneous rate of fishing mortality that provides for the Maximum Sustainable Yield) has been considered to be a recommendable approach to meet the fisheries management objectives. Fishing at F_{MSY} has been shown to provide a yield close to the maximum obtainable by any strategy (Gets et al., 1987; Hall et al., 1988), and the definition of the F_{MSY} rule has been included in most fishery management plans. For example, management plan developed by U.S. Fishery Management Councils include definitions of a maximum sustainable yield (MSY) rule. The rule describes a constant fishing mortality rate that maximizes the long-term average yields (F_{MSY}), as well as an optimal yield rule that reduces fishing mortality when stock size is below the mean biomass at F_{MSY}, namely B_{MSY} (NPFMC, 2004). Since obtaining a reliable estimate of the F_{MSY} for a particular fish stock is difficult, proxies are established for F_{MSY} and B_{MSY} based on spawning biomass per recruit (Dorn, 2002). In the U.S. fisheries management system, an ABC for demersal fish such as rockfish, would be based on a harvest rate of $F_{40\%}$. This rate, which reduces the probability of low biomass if recruitment were highly variable or autocorrelated (Clark, 1993), would be substituted for the F_{MSY} proxy. In the Korean fisheries management system, since more than 250 species of fish are exploited in the seas adjacent to Korea, estimated rates of $F_{35\%}$ and $F_{30\%}$ fishing mortalities have been adopted to set the ABCs for demersal and pelagic stocks, respectively, as proxies for F_{MSY} (Zhang & Marasco, 2003). Once the ABCs are reached, these species are prohibited to be caught and must be returned to the sea in the Korean management system. Any level, however, was not defined which the fishery is closed when the harvest reaches in spirit of precautionary approaches. This level will provide the concept of overfishing in the Korean management procedure, which is defined as any amount of fishing in excess of a prescribed maximum allowable rate.

The purpose of this chapter is to investigate and evaluate an optimal harvest rate, to define a maximum fishing mortality threshold (MFMT), and to develop a tier system for application of harvest control rules for jack mackerel in Korean waters. I calculated the optimal harvest rate that provides a yield near MSY for any probable spawner-recruit relationship (SRR) and estimated the spawning biomass per recruit (SPR) harvest rate required for establishing an F_{MSY} proxy for jack mackerel. Based on the optimal harvest rate, I defined a MFMT that would prevent overfishing while still achieving, on a continuing basis, an optimal yield from the major jack mackerel fishery. Finally for potential refinement of the present management system, a revised five-tier system was developed with depending on the quality and quantity of information available that includes an overfishing level (OFL) as well as acceptable biological catch (ABC) of jack mackerel around Korean waters.

4.2 MATERIALS AND METHOD

The customary formulations of the spawner-recruit relationship (SRR) or curves for fish species were considered initially as sets of equations, and associated graphs or curves, known as asymptotic Beverton-Holt SRR (BH-SRR) and the dome-shape Ricker SRR (R-SRR). The traditional formulations of the spawner-recruit curves for fish species described recruitment as a function of spawning biomass relative to unfished levels (Clark, 1991). This study considered both the R-SRR and BH-SRR for jack mackerel and included environmental factors, such as zooplankton biomass and temperature that described effects of recent environmental conditions (Fig. 3-19). The re-written SRR formulations were:

Ricker SRR : $(R/R_0) = (S/S_0) \cdot e^{\beta S_0(1-S/S_0)+\varepsilon}$

Beverton-Holt SRR : $(R/R_0) = (S/S_0)/[1-\beta S_0(1-S/S_0)] \cdot e^{\varepsilon}$

where, S_0 denotes the equilibrium spawning biomass in the absence of fishing, R_0 is the corresponding unfished level of recruitment and ε is random error, so that relative recruitment (R/R_0) was given as a function of relative spawning biomass (S/S_0) and the single shape parameter βS (Kimura, 1988). The equations were changed to be

Ricker curve : $(R/S) = (R_0/S_0) \cdot e^{\beta S_0(1-S/S_0)+\varepsilon}$

Beverton-Holt curve : $(R/S) = (R_0/S_0)/[1-\beta S_0(1-S/S_0)] \cdot e^{\varepsilon}$,

which provided the means of solving for the equilibrium spawning biomass at any fishing mortality rate F. The ratios (R_0/S_0) and (R/S) were the reciprocal of spawning biomass per recruit in the absence of any fishing and when F is applied, respectively. Once these ratios have been computed, the spawner-recruit (S-R) equation can be solved for (S/S_0) (Clark, 1991).

The unfished spawning stock size was estimated from recent recruitment levels and the unfished spawning biomass per recruit was calculated from life history parameters (Table 4-1). For both forms of the SSR relationship, the shape parameters (βS) were used with the "steepness" parameters of Mace (1993). These parameters are a useful metric for the degree of compensation in the S-R relationship and are of potential use in stock assessment modeling and in Monte Carlo simulation to evaluate rebuilding plans and harvest policies (Dorn, 2002). The initial values of S-R curve shape were 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, and 0.40 to explore diverse shapes. If all of the S-R curves had to be considered, there would clearly be no possibility of choosing a compromise fishing mortality rate that would serve reasonably well for all of the yield curves. But some of the S-R relationships can be ruled out on the basis of experience and common sense (Clark, 1991). Clark (1991) showed it was reasonable to exclude the lower pair of S-R curves, such as F_{MSY} values less than 0.1, and the upper pair of S-R curves, such as more than 0.3, and the least density-dependent pair S-R curves drove fish stock to extinction and the uppermost pair of S-R curves expected to reduce recruitment and yield dramatically. With the extreme portion of the initial range of S-R relationships excluded, it was possible to choose a fishing mortality range that would provide a large fraction of MSY regardless of which of the remaining S-R

Table 4-1. Life history parameters of jack mackerel in Korean waters

Age	Natural mortality[1]	Proportion mature[2]	Proportion recruited[3]	Average body weight (g)[4]
0	0.58	0.00	0.03	21.5
1	0.58	0.15	0.52	83.8
2	0.58	0.40	0.99	177.4
3	0.58	0.80	0.87	286.1
4+	0.58	0.95	0.82	396.5

Source 1. Natural mortality at age is assumed to be constant,

2. Proportion mature denotes maturity at age,
3. Proportion recruited indicates mean fishing morality normalized to the maximum at age in the biomass-based cohort analysis, i.e. selectivity at age,
4. Average body weight is converted from the von Bertalanffy growth equation of jack mackerel (L_∞ = 42.49cm, K= 0.248/year, t_0= -0.809 year)

curves was correct (Clark, 1991).

Yield per recruit and spawning biomass per recruit were calculated for each value of F. For each S-R curve and each value of F, equilibrium spawning biomass and recruitment were determined by solving the S-R equation, and relative yield (Y / MSY) was obtained from absolute yield as $Y = R \cdot (Y / R)$ for each F and maximum yield for each S-R curve.

4.3 RESULTS

4.3.1 Optimal Harvest Rate from Spawner-Recruit Relationships

The yield curves corresponding to the initial S-R curves are extremely diverse, with F_{MSY} values ranging from less than 0.1 to almost 1.0. I excluded the extreme parts of the initial range of S-R curves at both the upper and lower ends and chose a remaining subset of the initial SRR which provided F_{MSY} values in the range of 0.10 to 0.20 to serve as a reasonable approximation (Fig. 4-1). There was a level of spawning biomass per recruit that provided a large fraction or about 75% of MSY even under the least favorable selected S-R curves. This was shown as the "*maximin* yield" in Fig. 4-1 because it was the 'maximum' of the 'minimum' yields at each level of spawning biomass per

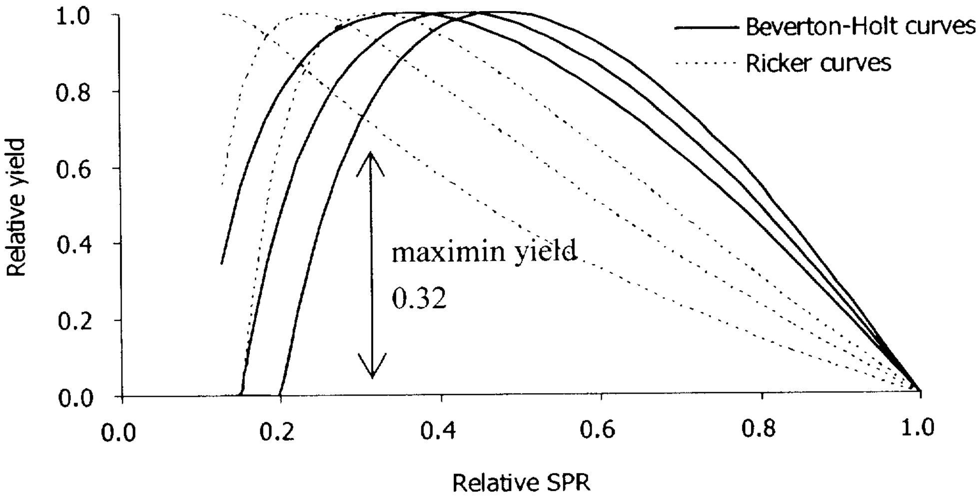

Fig. 4-1. The maximum of the minimum (*maximin*) yields at each level of spawning biomass per recruit of jack mackerel around Korean waters.

recruit. In other words, it was the maximum of the minimum yields at each rate of fishing mortality. The *maximin* yield about 75% of MSY was provided at 32% of the unfished value of spawning biomass per recruit, which corresponds to a fishing mortality rate of 0.50, denoted F_{mmy} as defined by Clark (1991). Considering the presence of uncertainty in the stock-recruit relationship, I defined optimal harvest rate of jack mackerel to be within the range of 30-35% of the unfished level of SPR (Fig. 4-2).

4.3.2 Harvest Control Rule

Based on the optimal harvest rate of 0.44-0.55/year occurring at 30-35% of the unfished value of spawning biomass per recruit (Fig. 4-2), an acceptable biological catch (ABC) and overfishing level (OFL) for jack mackerel fisheries were defined. The ABC is a preliminary description of the acceptable harvest for jack mackerel stock, focusing on the status and dynamics of the stock plus environmental conditions. Overfishing was defined as any rate of fishing in excess of the maximum fishing mortality threshold (MFMT). OFL was a catch corresponding to fishing at a rate equal to the MFMT. Fishing mortality rate corresponding to B_{MSY} or $B_{30\%}$ as a proxy of B_{MSY} could be defined as F_{OFL}, while the rate to $B_{35\%}$ be F_{ABC} (Fig. 4-3). Once the biomass of

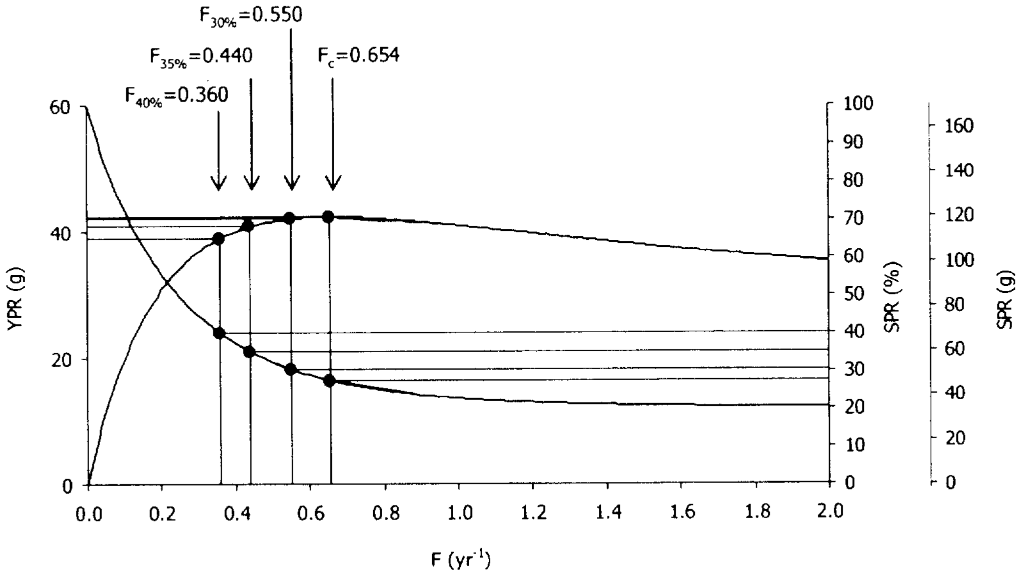

Fig. 4-2. Estimates of biological reference points ($F_{40\%}$, $F_{35\%}$, $F_{30\%}$) and current F (F_c), fixing t_c at the current level of 0.53 year for jack mackerel in Korean waters and corresponding levels of percentages of spawning biomass and yield per recruit. F = instantaneous coefficient of fishing mortality, YPR = Yield per recruit, SPR = Spawning biomass per recruit.

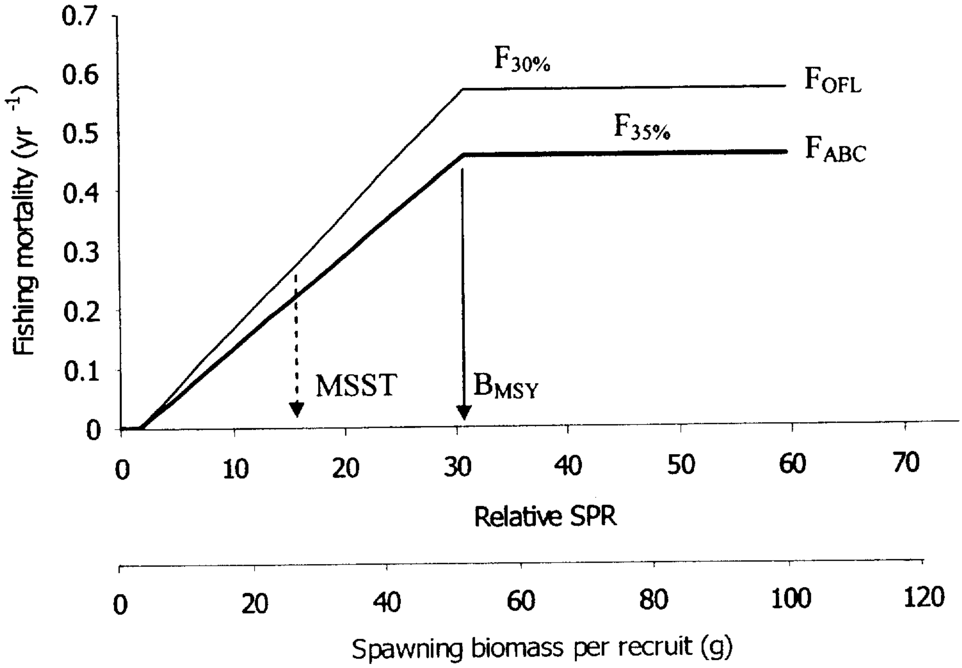

Fig. 4-3. Harvest control rules based on the *maximin* yield for jack mackerel around Korean waters.

jack mackerel falls below the minimum stock size threshold (MSST), where could be defined a half of B_{MSY} or $B_{30\%}$ as a proxy (dotted arrow in Fig. 4-3), then remedial management action is required to rebuild the stock to the MSY level within an appropriate time frame, generally not exceed 10 years for the short-lived pelagic jack mackerel.

These ABC and OFL values were used in a set of five tiers in descending order of information availability (Table 4-2). These tiers take into account the quantity and quality of data available and the exploitation history of the fishery.

Information available in tier 1 is reliable historic estimates of biomass, M, B_{MSY}, F_{MSY}, $F_{35\%}$ and $F_{30\%}$ for jack mackerel plus environmental factors affecting recruitment. The information of B_{MSY} and F_{MSY} were not available, because the fit of the biomass-based approach to the production model (Zhang, 1991), using biomass and fishing mortality, were not statistically significant, so these vales could not be estimated. However, the best reliable current biomass, $B_{35\%}$, $F_{35\%}$, $F_{30\%}$ and M for jack mackerel plus environmental factors affecting recruitment were available to be used for tier 2 in this study (Table 4-3). The biomass of the jack mackerel stock around Korean waters was

Table 4-2. Tiers used to determine overfishing level (OFL) and acceptable biological catch (ABC) for jack mackerel in the Korean TAC fisheries management system

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Tier 1. Information available : Reliable estimates of B, B_{MSY}, F_{MSY}, $F_{35\%}$, $F_{30\%}$ and environmental factor

1a) Stock status : $B/B_{MSY} > 1$

$F_{OFL} = F_{MSY}$

$F_{ABC} = F_{MSY} \times (F_{35\%}/F_{30\%})$

1b) Stock status : $\alpha < B/B_{MSY} \leq 1$

$F_{OFL} = F_{MSY} \times (B/B_{MSY} - \alpha)/(1 - \alpha)$

$F_{ABC} = F_{MSY} \times (F_{35\%}/F_{30\%}) \times (B/B_{MSY} - \alpha)/(1 - \alpha)$

1c) Stock status : $B/B_{MSY} \leq \alpha$

$F_{OFL} = 0$

$F_{ABC} = 0$

Tier 2. Information available : Reliable estimates of B, $B_{35\%}$, $F_{35\%}$, $F_{30\%}$ and environmental factor

2a) Stock status : $B/B_{35\%} > 1$

$F_{OFL} = F_{30\%}$

$F_{ABC} = F_{35\%}$

2b) Stock status : $\alpha < B/B_{35\%} \leq 1$

$F_{OFL} = F_{30\%} \times (B/B_{35\%} - \alpha)/(1 - \alpha)$

$F_{ABC} = F_{35\%} \times (B/B_{35\%} - \alpha)/(1 - \alpha)$

2c) Stock status : $B/B_{35\%} \leq \alpha$

$F_{OFL} = 0$

$F_{ABC} = 0$

Tier 3. Information available : Reliable estimates of B, $F_{0.1}$ and environmental factor

$F_{OFL} = F_{0.1}$

$F_{ABC} = 0.75 \times F_{0.1}$

Tier 4. Information available : Time-series catch and effort data

4a) Stock status : $CPUE/CPUE_{MSY} > 1$

OFL = MSY

ABC = 0.75 ×MSY

4b) Stock status : $\alpha < CPUE/CPUE_{MSY} \leq 1$

$OFL = MSY \times (CPUE/CPUE_{MSY} - \alpha)/(1 - \alpha)$

$ABC = MSY \times 0.75 \times (CPUE/CPUE_{MSY} - \alpha)/(1 - \alpha)$

4c) Stock status : $CPUE/CPUE_{MSY} \leq \alpha$

OFL = 0

ABC = 0

Tier 5. Information available : Reliable catch history

OFL = Y_{AM} (arithmetic mean catch over an appropriate time period)

ABC = 0.75 × OFL

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1) Equation used to determine OFL in tiers 1-3:

$$OFL = OFL_r + \sum_{i=r+1}^{t_L} \frac{B_i F_{OFL} s_i}{M + F_{OFL} s_i}(1 - e^{-(M + F_{OFL} s_i)})$$

$$OFL_r = \frac{R F_{OFL} s_r}{M + F_{OFL} s_r}(1 - e^{-(M + F_{OFL} s_r)}),\ R_t = f(SB_{t-1}, E_{j_{t-1}})$$

2) Equation used to determine ABC in tiers 1-3:

$$ABC = ABC_r + \sum_{i=r+1}^{t_L} \frac{B_i F_{ABC} s_i}{M + F_{ABC} s_i}(1 - e^{-(M + F_{ABC} s_i)})$$

$$ABC_r = \frac{R F_{ABC} s_r}{M + F_{ABC} s_r}(1 - e^{-(M + F_{ABC} s_r)}),\ R_t = f(SB_{t-1}, E_{j_{t-1}})$$

where, B_i: Biomass at age i, M: instantaneous coefficient of actual mortality, F_{OFL} and F_{ABC}: instantaneous coefficients of fishing mortality determined by the data available and the stock status, s_i: selectivity at age i, r: recruit age, t_L: maximum fishing age

3) For tiers 1, 2 and 4, α is set at a default value of 0.05.

Table 4-3. OFL and ABC estimates in tier 2 for jack mackerel in the Korean TAC fisheries management system

	Stock status	OFL (mt)	ABC (mt)
Without environmental factors	$B/B_{35\%} = 0.785 \leq 1$, B = 682,346mt, $F_{35\%} = 0.440$/yr, $F_{OFL} = 0.425$/yr, $F_{ABC} = 0.340$/yr, M = 0.576/yr	183,392	152,068
With environmental factors	$B/B_{35\%} = 0.719 \leq 1$, B = 625,053mt ($B_i$ = 458,809, R = 166,245), $F_{35\%} = 0.440$/yr, $F_{OFL} = 0.387$/yr, $F_{ABC} = 0.310$/yr, M = 0.576/yr	196,726	162,635

available for each of ages 1 to 4 and older from 1968-2004. The current estimate of biomass was assumed to be the 2004 biomass of 682,346 mt and the biological reference point of $F_{35\%}$ was determined to be 0.440/year (Fig. 4-2). Since the stock status of jack mackerel with the ratio $B/B_{35\%}$ was 0.785, tier 2b was used to determine F_{OFL} and F_{ABC} as 0.425/year and 0.340/year, respectively. The OFL and ABC for jack mackerel stock around Korean waters were determined to be 183,392 mt and 152,068 mt, respectively (Table 4-3).

When environmental factors were incorporated with the SRR, the biomass at recruited age (age 1) in 2004 was fixed at the recruitment (*R*) of 166,245 mt, and the biomass at other ages was 458,809 mt. Therefore, the current biomass with environmental factors was calculated as 625,053 mt. Since the stock status of jack mackerel with the ratio $B/B_{35\%}$ was 0.719, tier 2b was used to determine F_{OFL} and F_{ABC} with 0.387/year and 0.310/year, respectively. Finally, the OFL and ABC with environmental factors influencing to jack mackerel stock around Korean waters were estimated to be 196,726 mt and 162,635 mt, respectively (Table 4-3).

4.4 DISCUSSION

A harvest rate based on spawning biomass per recruit is explicitly intended to protect stocks from recruitment overfishing (Dorn, 2002). An SPR-based harvest rate will also harvest unproductive stocks at lower rates than productive stocks (Clark, 1991). For these reasons, the Korean fisheries management system adopted a SPR-based harvest rate to estimate optimal harvest limit for the TAC-based fishery management (Zhang & Lee, 2001; Zhang et al., 2000). However optimal harvest rates, that is, $F_{30\%}$ for pelagic and $F_{35\%}$ for demersal fisheries resources were not investigated, nor were the procedures for estimating optimal harvest rates. A set of five management tiers in the Korean TAC fisheries management system did not define overfishing levels. This study investigated the approved the harvest rates of $F_{30\%}$ and $F_{35\%}$ and found that they were plausible for the fishing mortalities at the levels of OFL and ABC for jack mackerel around Korean waters.

The F_{mmy} (fishing mortality at the *maximin* yield in Fig. 4-1) took about 75% of MSY if either of the extreme S-R curves applied, and it took 90% or more of MSY if one of the intermediate S-R curves applied in this study. The F_{mmy} for jack mackerel was high because growth was rapid and older age-classes than age 2 were more than 80% vulnerable to the fishery (Table 4-1). These results illustrate the importance and utility of determining the effect of a given fishing pattern on spawning biomass per recruit to avoid overfishing but also to avoid underfishing (Clark, 1991).

Incorporating environmental factors in stock assessment is important, especially for the pelagic stocks, which are sensitive to changes in environmental conditions. For example, OFL and ABC estimated by incorporating environmental factors, were 13,334 and 10,567 mt higher, respectively, than those estimated with customary formation of the spawner-recruit relationships in tier 2 under favorable marine environmental condition for jack mackerel. Better information, including good environmental indicators for jack mackerel, allows stock assessment scientist to avoid underestimating the stock status and to achieve more accurate assessment.

Japanese ABCs, pooled from Korean and Japanese fishery data, were estimated to be 188,000 and 161,000 mt at the limit and target level, respectively, in 2004 (JFRA, 2004). Those optimal harvest ranges were similar to the ranges of the ABC and OFL, 152,000-183,000 mt, estimated from pooled fishery data from Korea and Japan in this study (Table 4-3). Since the harvest limit for each country was somewhat different, each quota was divided by recent mean catch proportion, that is, 14.8% for Korea versus 85.2% for Japan (Table 4-4). These differences between the two countries could be caused from differences in biomass estimation, optimal harvest rate and harvest control rules. Japan estimated biomass as 415,000 mt, while this study estimated it as 676,000 mt. While Japan set the harvest rate in the range of 0.57-0.71 from 0.8-1.0 of current F, while this study set the optimal harvest rate in the range of 0.34-0.43 without environmental factors or 0.31-0.39 with environmental factors from the range of OFL-ABC (Table 4-4). For a practical and effective management of the jack mackerel stock, a straddling stock around Korean waters, a joint stock assessment and management system with unified information and common methodology should be established. Such a process could be the only way to ensure appropriate utilization and conservation of this valuable pelagic fish stock.

Table 4-4. Comparison of harvest ranges estimated by Japan and this study around Korean waters

		This study		Japan FRA (2004)	
		OFL	ABC	ABC_{limit}	ABC_{target}
Without environ. factors	Total	183,392	152,068	188K	161K
	Korea	27,226	22,576	23K	19K
	Japan	156,165	129,492	165K	142K
With environ. factors	Total	196,726	162,635	-	-
	Korea	29,206	24,145	-	-
	Japan	167,520	138,490	-	-

4.5 LITERATURE CITED

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CHAPTER 5

SUMMARY AND CONCLUSION

I developed a spawning stock-recruitment relationship that incorporated environmental factors and examined environmental factors that could affect the biomass of jack mackerel. These analyses that consider environmental shifts in Korean waters are necessary in order to estimate acceptable biological catch and overfishing level for jack mackerel, and develop a sustainable harvest strategy.

Physical ocean environments were examined using seawater temperature, salinity and density at surface and 50m layer depth from 157 stations over 38 years. Three water properties, corresponding to the East Sea, East China Sea, and Yellow Sea of Korea, were categorized by self-organizing mapping (SOM) and wavelet spectra of three water-properties exhibited strong decadal frequencies of 8-16 years from the late 1970s to the late 1980s.Ocean surface current drifted westwards during the 1980's and moved eastwards to the western area of Kyushu of Japan during the 1990's. Zooplankton biomass, one of major biological ocean environment factors, showed a positive significant correlation with local scale physical environment, such as sea water temperature in major habitat of jack mackerel and with global scale physical environment, such as PDO and SOI indices.

Based on the hypothesis of advection-based recruitment, successful recruitment was dependent on the abundance and distribution of spawning biomass in the previous year, food availability and temperature in the major habitat of jack mackerel. Discontinuity was tested in ocean environmental time series relative to the catch, recruitment and biomass at age of jack mackerel for 1968-2004. The spawning biomass and recruitment relationship of jack mackerel shifted in 1976 and 1987, and the recruitment estimate considering three regimes was very significantly correlated with recruitment of jack mackerel ($P<0.001$).

Generalized additive models (GAM) were developed to explore relationships between jack mackerel recruitment, spawning biomass and environmental variables in the major habitat area of jack mackerel around Korean waters. The time-series of estimated recruitment by the function of *loess* with spawning biomass, zooplankton biomass and PDO provided the best explanation for the period of 1989-2003.

I constructed the annual weight at age for 1968-2004 and used them to estimate biomass of jack mackerel with the biomass-based cohort analysis. The biomass and instantaneous fishing mortality with the constant weight at age calculated from von Bertalanffy growth parameters and length-weight relationship overall periods were underestimated in comparison of those with annual weight at age, especially when the biomass was high the bias was higher.

I investigated and evaluated an optimal harvest rate, and developed a tier system for application of harvest control rules for jack mackerel around Korean waters. I calculated the optimal harvest rate of jack mackerel to be within the range of 30-35% of the unfished level of spawning biomass per recruit (SPR) that provides a yield near MSY for any probable spawner-recruit relationship (SRR) and estimated the SPR harvest rate required for establishing an F_{MSY} proxy for jack mackerel. This study investigated the approved the harvest rates of $F_{30\%}$ and $F_{35\%}$ and found that they were plausible for the fishing mortalities at the levels of OFL and ABC for jack mackerel around Korean waters.

Based on the optimal harvest rate, I defined a maximum fishing mortality threshold (MFMT) that would prevent overfishing while still achieving an optimal yield form the major jack mackerel fishery. For potential refinement of the present management system, I developed a set of five tiers that includes an overfishing level (OFL) as well as acceptable biological catch (ABC) of jack mackerel around Korea waters.

OFL and ABC estimated with incorporating environmental factors were 13,334 and 10,567 mt higher, respectively, than that estimated with customary formation of the SRR in tier 2 under favorable marine environmental conditions for jack mackerel around Korean waters.

Japanese FRA estimated ABCs with pooled Korean and Japanese fishery data to be about 161,000 and 188,000 mt at the target and limit level, respectively, in 2004. Those optimal harvest ranges were similar to the ranges of the ABC and OFL, c.a. 152,000 and 183,000 mt, estimated from pooled fishery data from Korea and Japan, in this study. Since the harvest limit for each country was somewhat different, each quota was divided by recent mean catch proportion, that is, 14.8% for Korea versus 85.2% for Japan. These differences between the two countries could be caused from differences in biomass estimation, optimal harvest rate and harvest control rules. Japan estimated biomass as 415,000 mt, while this study estimated it as 676,000 mt. While Japan set the harvest rate in the range of 0.57-0.71 from 0.8-1.0 of current F, while this study set the optimal harvest rate in the range of 0.34-0.43 without environmental factors or 0.31-0.39 with environmental factors from the range of OFL-ABC. For a practical and effective management of the jack mackerel stock, a straddling stock around Korean waters, a joint stock assessment and management system with unified information and common methodology should be established. Such a process could be the only way to ensure appropriate utilization and conservation of this valuable pelagic fish stock.